Utilization of IoT technologies in electricity distribution network management

Mika Suomi

School of Electrical Engineering

Thesis submitted for examination for the degree of Master of Science in Technology.

Espoo 16.4.2018

Thesis supervisor:

Prof. Matti Lehtonen

Thesis advisor:

M.Sc. Antti Keskinen

Aalto University
School of Electrical
Engineering

AALTO UNIVERSITY
SCHOOL OF ELECTRICAL ENGINEERING

ABSTRACT OF THE
MASTER'S THESIS

Author: Mika Suomi

Title: Utilization of IoT technologies in electricity distribution network management

Date: 16.4.2018 Language: English Number of pages: 6+104

Department of Automation and Electrical Engineering

Professorship: Power systems and high voltage engineering

Supervisor: Prof. Matti Lehtonen

Advisor: M.Sc. Antti Keskinen

Objective of this thesis is to define and assess changes in energy sector which will directly or indirectly affect distribution grid operation and management in Finland, and to determine measurable events or variables which enable identification and monitoring of the recognized changes. Based on assessment of the upcoming changes, possibilities for utilizing IoT technologies in management and monitoring applications of the identified changes are assessed.

In the assessment of upcoming changes, total of eight subjects were covered and microgeneration, electric vehicles and heat pumps were identified to be the most probable changes to realistically penetrate Finnish energy sector within a time scope of approximately 10 years. However, none of the assessed changes were found to have significant and wide-scale effects in terms of performance of Finnish distribution networks.

For utilization of IoT technologies in distribution networks one application for operational grid monitoring of power quality problems derived from residential photovoltaic generation, and three cases for IoT based asset health and condition monitoring were assessed. Furthermore, requirements and architecture for data storage and analysis platform of IoT based system were discussed. From the evaluated applications, condition monitoring scheme of circuit breakers was determined to be the most promising alternative.

Keywords: Internet of Things, IoT, Distribution networks, Microgeneration, Electric vehicels, Heat pumps, Asset health, Condition monitoring

AALTO-YLIOPISTO
SÄHKÖTEKNIIKAN KORKEAKOULU

DIPLOMITYÖN
TIIVISTELMÄ

Tekijä: Mika Suomi

Työn nimi: IoT-teknologian hyödyntäminen sähköverkko-omaisuuden hallinnassa

Päivämäärä: 16.4.2018 Kieli: Englanti Sivumäärä: 6+104

Automaatio- ja sähkötekniikka

Professuuri: Sähköverkot ja suurjännitetekniikka

Työn valvoja: Prof. Matti Lehtonen

Työn ohjaaja: DI Antti Keskinen

Diplomityön tavoitteena on määritellä ja arvioida energiasektoriin vaikuttavien tulevien muutosten suoria tai epäsuoria vaikutuksia jakeluverkon toimintaan ja hallintaan. Havaittujen muutosten vaikutuksista on tarkoitus tunnistaa mitattavia ilmiöitä tai suureita, jotka mahdollistavat muutosten tunnistamisen sekä seurannan. Muutosanalyysiin pohjautuen tavoitteena on tunnistaa ja arvioida mahdollisuuksia IoT-teknologian hyödyntämiseksi havaittujen muutosten aiheuttamien ongelmakohtien tai mahdollisuuksien tunnistamisessa, seurannassa sekä hallinnassa.

Energiasektoriin vaikuttavien muutosten analyysissä arvoitiin kokonaisuudessaan kahdeksaa eri aihealuetta ja lopputuloksena pientuotannon, sähköautojen sekä lämpöpumppujen todettiin olevan todennäköisimmät teknologiat, jotka yleistyvät merkittävissä määrin suomalaisessa sähköverkossa seuraavan kymmenen vuoden aikana. Minkään käsitellyn muutoskohdan ei kuitenkaan todettu aiheuttavan laajamittaisia ja merkittäviä ongelmia jakeluverkon toimintaan.

IoT-teknologian hyödyntämiseen jakeluverkkotoiminnassa käsiteltiin yhtä verkon käyttöön ja sähkön laatuun liittyvää sovellusta, jonka avulla hajautetun pienaurinkotuotannon vaikutuksia pystytään seuraamaan, sekä lisäksi kolmeen eri verkkokomponenttiin kohdistuvaa jatkuvan kunnon seurannan sovellusta. Tämän lisäksi IoT-järjestelmän toteuttamiseksi vaadittavalle analyysi- ja tietojärjestelmäalustalle määriteltiin rakenteellisia ja toiminnallisia tarpeita. Työssä käsitellyistä IoT-sovelluksista lupaavimmaksi todettiin katkaisijoihin kohdistuva jatkuvan kunnonhallinnan sovellus.

Avainsanat: Asioiden internet, IoT, Jakeluverkot, Pientuotanto, Sähköautot, Lämpöpumput, Jatkuva kunnonvalvonta, Omaisuudenhallinta

Preface

This thesis was written as a commission for Caruna Oy during the time between September 2017 and February 2018.

I would like to express my gratitude to the number of people at Caruna who have supported and helped me during this process. Especially I would like to thank my advisor Antti Keskinen for providing me with an opportunity for writing this thesis and offering me an interesting subject to focus on.

I would also like to thank my supervisor Matti Lehtonen for offering me his expertise and helping me during my writing process.

Finally, I would like to express gratitude for my whole family for supporting me during my entire studies and enabling me to enjoy academic life both in Finland and abroad.

Otaniemi, 13.4.2018 Mika Suomi

Contents

Abstract ii

Abstract (in Finnish) iii

Preface iv

Contents v

Abbreviations vi

1 Introduction 1

2 Changes affecting distribution networks 4
2.1 Investments in security of supply . . . 4
2.1.1 Construction principles of the new grid . . . 4
2.1.2 Impact to network faults . . . 5
2.1.3 Impact to component dimensioning . . . 7
2.1.4 Earth fault current and reactive power compensation . . . 7
2.1.5 Impact of compensation methods . . . 8
2.2 Electric vehicles . . . 9
2.2.1 Adoption of EVs in Finland . . . 9
2.2.2 Charging of EVs . . . 10
2.2.3 Impact on distribution system . . . 12
2.2.4 Load effects . . . 13
2.2.5 Power quality . . . 15
2.3 Heat pumps . . . 16
2.3.1 Heat pumps in Finland . . . 16
2.3.2 Impact on distribution system . . . 17
2.3.3 Load effects . . . 18
2.3.4 Power quality . . . 20
2.4 Electrical energy storage . . . 20
2.4.1 Properties of battery energy storages . . . 21
2.4.2 Application of domestic battery storage . . . 21
2.4.3 Grid impact of EES . . . 23
2.5 Microgeneration . . . 24
2.5.1 PV adoption in Finland . . . 25
2.5.2 Impact on distribution system . . . 27
2.5.3 Load effects . . . 28
2.5.4 Power quality . . . 31
2.6 Demand response . . . 32
2.6.1 Application of DR in Finland . . . 33
2.6.2 Impact on distribution system . . . 34
2.7 Data analytics and utilization . . . 38
2.7.1 Load profile estimation and classification . . . 38

2.7.2 Data utilization in network planning . . . 39
2.7.3 Asset health and condition-based maintenance . . . 40
2.8 Energy communities . . . 42
2.8.1 Estimation based cost allocation . . . 45
2.9 Summary of the impacts . . . 46

3 Introduction to IoT 53
3.1 Development and trends . . . 53
3.2 Architecture of IoT system . . . 54

4 Utilization of IoT technologies 57
4.1 Architecture design for IoT based monitoring system . . . 57
4.1.1 Sensors and communication . . . 57
4.1.2 Data analysis and system integration . . . 60
4.1.3 Application layer . . . 61
4.2 Possibility for power quality measurements with AMR meters . . . 62

5 Asset health and condition monitoring system 65
5.1 Motivation for condition monitoring . . . 65
5.2 Circuit breaker condition monitoring . . . 66
5.2.1 Suggestion for measurement parameters . . . 68
5.3 Secondary substation and distribution transformer condition monitoring 69
5.3.1 Suggestion for measurement parameters . . . 70
5.4 Underground cable condition monitoring . . . 72
5.4.1 Suggestion for measurement parameters . . . 74

6 Recognition of voltage quality issues in LV network 76
6.1 Voltage deviations . . . 76
6.1.1 PV system characteristics and protection . . . 77
6.1.2 PV generation dimensioning . . . 78
6.1.3 Probable areas with power quality issues . . . 79
6.2 Measurement strategy for LV network voltages . . . 79
6.2.1 Requirements for IoT-based voltage measurements . . . 81
6.2.2 Assessment of benefits . . . 82

7 Conclusion of IoT utilization 84

8 Summary 87

References 92

Abbreviations

AHI	Asset Health Index
AHP	Air-air heat pump
AMR	Automatic meter reading
API	Application programming interface
CB	Circuit breaker
CIC	Customer Interruption Cost
CIS	Customer Information System
COP	Coefficient of performance
DC	Direct current
DGA	Dissolved Gas Analysis
DMS	Distribution Management System
DR	Demand response
DSO	Distribution system operator
EES	Electrical energy storage
EV	Electric vehicle
GHG	Greenhouse gas
GHP	Ground source heat pump
HP	Heat pump
HV	High voltage
IoT	Internet of Things
LoM	Loss of Mains
LV	Low voltage
MV	Middle voltage
NIS	Network Information System
OHL	Overhead Line
OPEX	Operational Expenditure
PLC	Power Line Communication
PV	Photovoltaic
SCADA	Supervisory Control And Data Acquisition
V2G	Vehicle-to-Grid
WSN	Wireless Sensor Network

1 Introduction

Electrical power system is undergoing profound changes which are believed to have significant effects on electricity grid operation, quality of the supplied power and mechanical durability of the grid components. These changes are fundamentally driven by the global climate change mitigation goals which have created a need for more efficient and environmentally friendly ways of generating, distributing and consuming energy. Finland is one of the 175 countries that have signed the Paris climate agreement and is therefore committed to reducing greenhouse gas emissions in order to restrain global warming to 1,5 °C. It is widely believed that the upcoming changes to the power system will have profound implications especially to the electricity distribution grids and that significant effort and investments will have to be made in order to cope with these changes.

Some of the anticipated challenges in terms of distribution networks are linked to the changing consumption patterns and increasing amount of distributed small scale electricity generation, such as solar and wind power. It is also likely that peak loads will increase and traditional consumption patterns will be disturbed. For the power system to function properly, the amount of electric power generation and consumption must match at all times. Traditionally this equilibrium has been maintained by controlling the generation of large thermal or hydro power plants. Due to the increasing amount of distributed and volatile renewable generation, the power system can no longer be controlled in a traditional top-to-bottom manner, but the power flow direction can momentarily change and control over the generation is lost.

New technologies, operational models and market mechanisms have been invented and proposed in order to cope with the mismatch of consumption and generation patterns. Concepts such as demand response (DR) and new market models such as flexibility market or communal energy systems have been developed. Furthermore, the use of electricity storage to compensate the mismatch of generation and consumption has been under development. However, these technologies are still under development and we are still to form consensus on what the future of our electrical power system and energy system will look like.

To some extent the effects of these changes to the power system can already be seen and for example the amount of electrical vehicles (EV) and distributed electricity production such as wind and solar power has already increased globally during the last decade. Even though in Finland the adaption of these technologies has been comparatively slow, current local and EU-wide political decisions are driving the transition forwards.

In addition to political drivers, a new power system architecture, fast development of information technologies and digitalization have modified, and are predicted to further modify the way transmission and distribution grids are operated. This shift towards more intelligent power system management and operation is globally referred to as "Smart Grid" which can be seen as an enabler of the grid integration for new technologies and operation models. However, Smart Grid as a term is rather vague and does not have a single unambiguous meaning. In fact, it is being used from simple cases such as introduction of automatic meter reading (AMR) systems, to the level where it includes everything from massive SCADA systems to transformer automation and demand response systems.

Fast development of "Smart" technologies and decrease in investment costs has enabled application of automation and remote metering to lower voltage levels of the distribution grid. Functionalities which were 20 years ago economically feasible only in high voltage (HV) network components, can now days be implemented to middle voltage (MV) and even low voltage (LV) networks.

The decrease in technology costs and advancements in sensor and communication technologies have also enabled a new level of metering and connectivity, as the required components and technologies are cheap enough for smart abilities and Internet connectivity to be applied in variable objects and assets in high volumes. This phenomenon is commonly referred to as Internet of Things (IoT) and its applicability is spread through all industries and is believed to revolutionize operations across number of different business sectors. It has been estimated that in year 2018 the number of Internet connected IoT devices will bypass the number of traditional mobile devices and that by year 2022 up to 50 % of all Internet connected devices will be IoT devices [1]. This goes to show the magnitude and potential that IoT technologies are expected to achieve.

Regardless of the high expectations for IoT, the technology is still under development and factors such as communication technologies are not yet fully defined. There are communication protocols such as LoRa and Sigfox currently available, specifically engineered for the use of IoT. These protocols are capable of connecting thousands of end devices to Internet and designed to be very energy efficient. It is however believed that the emergence of 5G communication technology will be a major enabler of the wireless IoT technology. Currently the existing applications are limited to only few industries such as packet delivery or waste management. However, the potential for IoT applications is significant in many industries, including the energy sector and electricity distribution.

Objective and structure of the thesis

Objective of this thesis is to define and assess changes in energy sector which will affect distribution grid operation and management in Finland, and to determine events or variables which enable identifying and monitoring the challenges arising from the changes to the power system. After identifying the possible problems caused by new technologies and operational models, possibilities of utilizing IoT sensor technologies in tracking and controlling the identified phenomenon are composed and assessed. Furthermore, system architecture possibilities for gathering and processing the collected data are discussed.

This thesis is made as a commission for Finland's largest distribution system operator (DSO) Caruna Oy. Therefore, the future problems and challenges concerning the distribution network will be assessed from the point of view of a Finnish distribution network. Globally the Finnish grid infrastructure has a reputation of being reliable, robust and efficient. Finland has been for example very quick to adopt network automation, AMR meters and SCADA systems as a part of distribution system. Furthermore, recent developments in regulation have resulted in extensive investments to redevelop the existing overhead lines into underground cables, which has had positive effects in terms of security of supply and at the same time the capacity of grid has improved.

As a result this thesis will provide a general understanding about the impact that emerging changes in energy sector will cause in the Finnish distribution system. Furthermore, the possibilities for managing and monitoring arising challenges will be defined and their overall feasibility assessed. Also, an overview of IoT system's architecture for processing and storing the received data will be presented.

In the second chapter of this thesis objective is to define the new technologies and operational models which will affect performance of distribution networks in the future. Goal is to gain insight about the gravity of upcoming changes in terms of Finnish grid infrastructure and to determine, how critical the anticipated challenges and problems will be for Finnish distribution networks. An other objective for this chapter is to identify physical variables or phenomena that can be used in order to locate, monitor or measure the problems that have been identified. Goal is to recognize concrete physical effects in the distribution network infrastructure that can be measured. By recognizing variables linked to the complications in the grid infrastructure, it is possible to determine the feasibility of applying IoT sensor technologies for management of these changes. Due to the wide scope of challenges affecting the distribution network, some subjects will have to be limited in terms of depth of the assessment. Subject specific exclusions will be defined at the beginning of the corresponding sections. Also, the assessment of effects to the electricity grid will be limited to the MV and LV levels of the grid including the possible effects in primary transformers.

In third chapter a short introduction to IoT technologies is provided. Recent capabilities as well as future expectations of IoT sector are discussed and few characteristic key indicators of the technology are presented. Also an overview of the architectural structure of a typical IoT system is presented and different levels of the system briefly explained.

In fourth chapter the architectural structure needed for IoT system realization in Caruna's case is assessed. Requirements for data processing data storage and integration of existing information systems is evaluated. Furthermore, an assessment about using existing AMR meters in data acquisition is provided.

In chapters five and six possible implementation cases for IoT based sensor technologies are determined and assessed from the point of view of an asset management based and grid operation based applications. The feasibility of the implementation will be mostly be evaluated from technical point of view, in respect to findings made in chapter two. Based on the technical assessment, of the chosen use cases a suggestions of an IoT based application schemes are provided. Finally, chapter seven provides conclusions of the IoT utilization cases.

2 Changes affecting distribution networks

In this chapter present and future changes affecting electricity distribution networks are assessed and compared. The impact of upcoming changes to quality of supplied electricity and physical condition of the network will be evaluated. Subjects for this evaluation have been chosen due to the general interest towards them in academic research, their popularity in local and global energy politics or because they are aligned with the strategy of the DSO in question.

The different technologies and practices are assessed in their own subsections. However, it is worth noting that the true implications of the emerging changes will often be tied or mixed together and therefore the effect of a single technology can not necessarily be accurately evaluated without a wider perspective. Therefore, the overall implications of the changes in question will be further discussed in the Summary subsection at the end of this chapter.

2.1 Investments in security of supply

Caruna is the largest distribution system operator in Finland with approximately 20 % market share of national electricity distribution market. Company operates mostly in southern, southwestern and western Finland with additional distribution areas in southern Lapland and city of Joensuu. Network areas consist of both rural and urban environments. Total amount of residential and business connection points in the network is little over 670 000. Network consists of 150 primary substations and 28 500 secondary substations with 28 300 km of MV lines and 51 700 km of LV lines connected to them.

Finnish distribution networks have traditionally been constructed largely from overhead lines with underground cables being used practically only in urban areas. However, as a consequence of large storms in the beginning of the decade wide electricity supply interruptions were encountered and therefore, in 2013 a new Electricity Market Act was introduced with tightened requirements for the security of supply. The new act sets strict limits for customer interruptions caused by weather events such as storms and high winds, which has led to significant security of supply investments in all DSOs in Finland. Implementation of the new security of supply article will begin in 2019 so the necessary investments will have to be made during the transitional period. [2]

2.1.1 Construction principles of the new grid

In practice, the most significant security of supply investments have focused in replacing of old OHL conductors with underground cables. As at the same time a large part of the existing OHLs are coming to the end of their life span, the investments result to an extensively high cabling rate in Caruna's distribution network, including MV and LV line sections. With underground cable network the likelihood of interruptions caused by weather events is marginal and furthermore, typically the life span of an underground cable is longer than that of an OHL.

Investment program started in 2012 first focusing primarily in renovation of MV network because of the higher significance of MV network faults to the customer interruption costs (CIC). Figure 1 shows the development of MV and LV network cabling rates in Caruna's network.

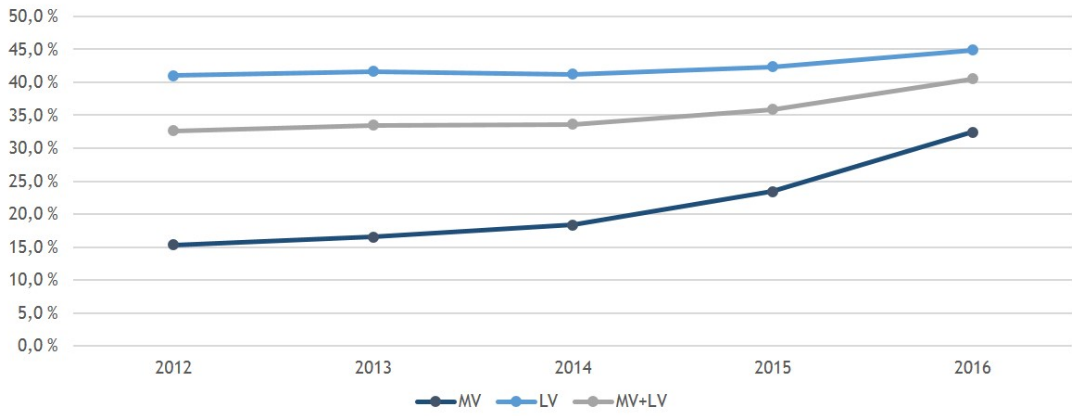

Figure 1: *Development of cabling rates in Carunas network during the last five years.*

In addition to high underground cabling quantities the grid will undergo other changes too. All pole-mounted distribution transformers in the grid will be replaced with pad-mounted transformer cabins on the ground. Also, topology of the grid will be improved by constructing ringed MV network whenever feasible, in order to increase the possibilities for backup connections in the grid. The density of manually and remotely operated switch disconnectors will also be increased. In urban networks all MV feeders of every secondary substation will be equipped with a switch disconnector and in every other substation the disconnectors will be remote-controlled. In rural areas the placement will be slightly less dense. This combined with increased possibilities for backup feeding will enable quicker response to possible faults in the grid and help to confine the impact area of possible interruptions.

2.1.2 Impact to network faults

Security of supply investments' impact is already starting to visualize in annual MV network fault rates. Total amount of encountered permanent faults in the whole MV network of Caruna has come down from the level of year 2012. Figure 2 presents the development of fault quantities in respect to the increasing cabling factor.

Similarly the impact of extensive cabling can be seen in the reasons behind the MV network faults, which are presented in figure 3. The amount of wind and storm originated supply interruptions has decreased from the start of the investment program. In addition, faults caused by lightnings as well as ice and snow have decreased. The amount of weather dependent interruptions can be expected to still further decrease as the cabling rate increases. Therefore, it is likely that the primary

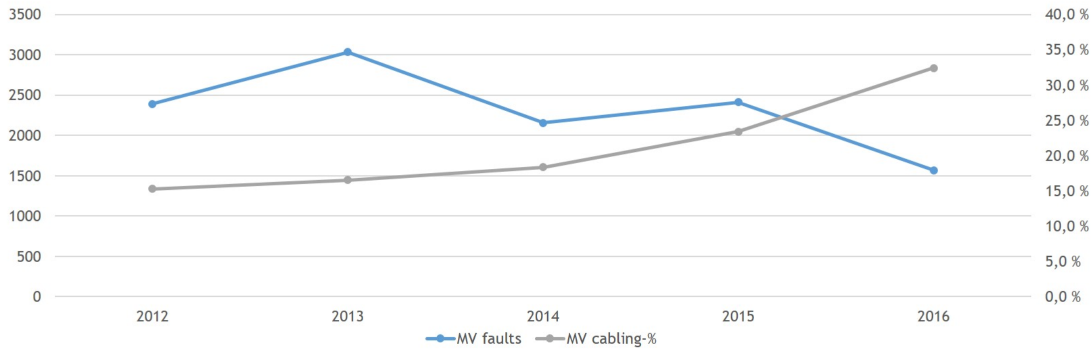

Figure 2: *Development of unexpected MV network interruptions in respect to MV cabling rate.*

reason of unexpected supply interruptions in the future will be structural defects and component malfunctions in the grid.

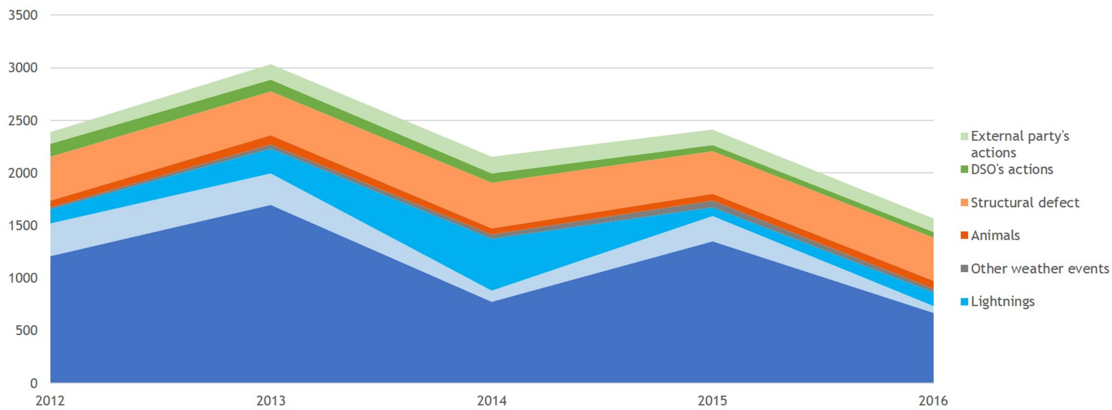

Figure 3: *Distribution of reasons behind unexpected MV network interruptions.*

With this in mind, the future focus in terms of security of supply can be allocated towards the surveillance of structural defects and network component condition management. After overhead lines, the biggest sources of faults in Caruna's network are underground cables and distribution transformers. Therefore, active asset health management could be applied to these components.

Condition monitoring can be executed by combining different direct or indirect measurements together. For example, health of distribution transformers can be monitored by combining heat, vibration, noise and operational data. [3] Similarly, cable health and faults such as insulation failures can be monitored with for example measurements of partial discharge or spatial temperature measurements. [4]

2.1.3 Impact to component dimensioning

In addition to improved security of supply, the new grid construction principles and high cabling rates introduce variety of other impacts to the grid. As large part of old overhead lines, of which many are coming to the end of their life-span, are replaced with underground cables, the dimensioning of the line sections as well as distribution transformers will systematically be corrected to answer the current and future needs.

The resulting grid will be significantly more robust than the old OHL network. The impact will be emphasized especially in rural networks, where network planning is mostly driven by voltage drop as a limiting factor instead of maximum load. This results to larger cross-sections in rural networks than would be required in terms of network load. In urban networks organic load growth and possible future peak load increase due to for example electric vehicles has been taken into account in network planning. For example overloaded or nearly overloaded distribution transformers have been upgraded in capacity according to the estimated future needs, which will likely reduce the problems concerned with increasing loads and load volatility.

2.1.4 Earth fault current and reactive power compensation

Cable network introduces also new issues in the distribution network. Compared to overhead lines, cable network produces large amounts of capacitive reactive power [5] and earth fault currents are also significantly higher [6]. Too large levels of reactive power are problematic because they congest the line sections by restricting the amount of active power flow and introduce reactive power losses. Also, in 2016 national transmission system operator (TSO) Fingrid Oyj announced new requirements concerning reactive power balance, which define reactive power supply and consumption limits for each transmission grid connection point individually. Reform introduces considerable costs for the DSO if the set limits are exceeded [7]. High earth fault currents on the other hand introduce increases in touch voltages throughout the network. Touch voltages are defined as the voltages that a person or an animal can experience when in contact with part of the network during an earth fault. Too high touch voltages will be dangerous for health and can produce currents that will cause ventricular fibrillation in human heart.

Compensation strategies for both issues have been developed in order to restrict these consequences. The resulting strategies are partly integrated together and based on centralized and distributed compensation solution. For the part of reactive power compensation, centralized shunt reactors are used, located at primary substations. Depending on the capacity and size of the feeding area in question the reactor is either connected to the primary or secondary side of the main transformer. Centralized reactors are remotely adjustable and the operation is managed through DSO's SCADA system. Each connection point to transmission grid is under individual an continuous surveillance by the TSO and the data is accessible for the DSO too.

Similarly, earth fault currents are compensated with partly centralized and partly distributed shunt reactors. Centralized shunt reactors in both, reactive power and earth fault current compensation, are principally similar appliances and according to the operation purpose different connection to the grid is used. Essentially reactive power compensation can be executed with three shunt reactors connected between three phases, disconnected from the earth potential. In earth fault compensation on the other hand, connection is executed with help of a single shunt reactor connected between the star point of an earthing transformer and ground potential. [5] [6] In theory, both compensation needs could be covered with one shunt reactor. However due to the large variances in reactive power compensation needs in different primary stations, it is more practical to implement both compensations with separate components.

The distributed compensation on the other hand is executed with combined use of smaller shunt reactors. Distributed compensation is spread out across the cable network and consists of reactors capable of compensating 5 – 15 A of earth fault current. Reactors are adjusted to appropriate settings according to the earth fault current production of the corresponding cable section. Essentially, the idea of the distributed compensation is to limit the increase of reactive power and earth fault current produced by cable network, while the centralized reactors respectively decrease them to desired levels.

2.1.5 Impact of compensation methods

Ideally the remotely controlled reactive power compensation units will be able to adjust the reactive power budget to the limits defined by the TSO. As the system is being over watched from the SCADA system, the desired reactive power balance should be easily set by network operation engineers.

The verification of acceptable touch voltage or earth fault current levels however is not currently possible through any active system already available. The verification is mostly based on calculations conducted based on the length and qualities of the supplying cable network, compensation equipment, earthing conditions of the geographical area as well as the density and classification of earthing in the area. Therefore, direct and real time information about the behavior of the touch voltages is not available. However, with further development of security of supply investments, some comprehensive measurements have been conducted in order to verify the functionality of the earth fault compensation strategy.

Functional earth fault current compensation can, in addition to ensuring the safety of the operated network, enable the operation of the grid during fault conditions. This is provided that appropriate functioning of earth fault currents can be verified and the touch voltages of the system do not exceed the limits set by regulation. [8] Comprehensive touch voltage measurements aim to do just that but execution of such tests throughout the whole distribution network would be economically not feasible. Therefore, for example continuous touch voltage or earth fault current metering, combined with the results from the extensive test measurements would help to justify and verify functionality of the compensation and therefore enable operation of the network in fault conditions. Continuous measurement points would enable extracting data from actual fault cases.

2.2 Electric vehicles

Electrification of transportation is globally a hot topic. Traditionally road transport can be considered to be fully operated by oil based fuels, but due to the fact that transportation fuels are a significant source of greenhouse gas emissions (GHG) and that the supply of oil will eventually have difficulties to keep up wit the demand, alternative ways for powering road vehicles have been developed. Therefore the introduction of EVs has become a major trend around the world and almost all major car companies are developing electric vehicles of their own. Globally the transportation sector is responsible for 23 % of GHG emissions [9] of which road transport vehicles account for about 75 % [10]. Therefore, it is evident that the pressure on emission reduction affects heavily on road transportation.

In 2016 total of 753 000 new electric vehicles were sold globally, raising the global amount of plug-in EVs in circulation to 2 million units. Approximately half of these new EVs were sold in China but Europe came in second with 215 000 sold units. This goes to show that European countries are at the forefront of adopting the use of electrical vehicles. [11] However, there are still boundaries that need to be overcome in order for EVs to become a realistic alternative for petrol powered vehicles. One problem is to do with the price of new EVs, as they tend to be significantly more expensive than traditional vehicles. Additionally, low driving range, availability of charging stations and long charging times of battery powered vehicles act as a barrier for many car owners. However, the fast development of battery technologies and charging infrastructure is believed to reduce these barriers. It is predicted that the amount of EVs will rise globally to the level of 30 million units by 2025 and 150 million units by 2040 [9].

2.2.1 Adoption of EVs in Finland

The adoption rate of EVs has been slow in Finland compared to rest of Europe or even other Nordic countries. At present there is only 1142 registered passenger EVs in Finland, while the total amount of registered vehicles is about 3 million units [12]. For comparison, in Norway EVs account for 29 % of light duty vehicles in the country [11], which goes to show that large scale adaption of electric vehicles is technically possible in Nordic countries.

In a study by VTT the composition and size of Finland's vehicle base has been predicted by a computational model that takes into account historical data about vehicle fleet and third party predictions about the development of different vehicle technologies. The model does not speculate any changes to the political incentives, so the forecast is composed using current vehicle sales statistics, policies and incentives. The model predicts that by year 2020 there would be 18 452 plug-in passenger vehicles on the road which represents only 0,7 % of the predicted total passenger car fleet at the time. By year 2030 the quantity would increase to 120 048 units corresponding to a 4,1 % penetration level. Figure 4 shows the predicted development of EV penetration in more detail. [13]

However, future political drivers are expected to enable accelerated penetration of EVs to Finnish vehicle fleet. According to Finnish Ministery of Economic Affairs

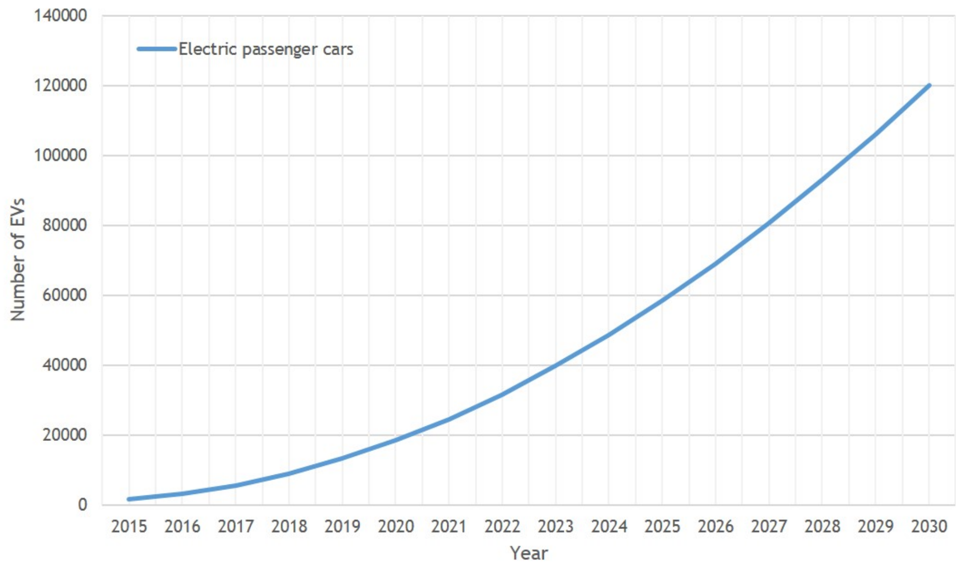

Figure 4: *Predicted penetration rate of electric and plug-in hybrid passenger vehicles in Finland.* [13]

and Emplotyment goal for Finland is to have 250 000 electric vehicles in circulation by the year 2030. [14] This goal is based on emission reduction goals in European Union countries which practically insist that significant reductions are needed from the transportation sector including passenger vehicles.

2.2.2 Charging of EVs

Charging of EVs is what essentially impacts electricity grid and therefore the different charging methods will be shortly presented. EVs can be charged with either a specified charging station or a standard wall socket connection. There are four different charging methods defined in an international standard IEC 61851-1 which can be used in EV charging [15]. Mode 1 relies on standard 230 V input voltage of a traditional socket reaching maximum currents of 16 A. It is intended for charging of light vehicles for short periods of time such as mopeds and electric bicycles. [16] Modes 2, 3 and 4 are charging methods intended for electric cars and therefore under focus of this thesis while mode 1 is left out of the assessment. Table 1 provides a summary of different charging modes and their functionalities.

Charging currents can vary from 6 A to 200 A with powers altering from 1,4 kW to 50 kW depending on the used charging mode. Charging mode 3 is intended to be the basic charging method for EV's everyday charging. It is an AC charging method that can alter currents between one-phased 6 A and three-phased 63 A with powers between 1,4 kW–43 kW. [16] It is also protected with safety functionalities and enables control of charging current. Furthermore, charging mode 3 enables vehicle-to-grid (V2G) operation or in other words feeding electricity back into the network from vehicle's battery storage. [17]

Table 1: *Charging modes intended for passenger car-sized EVs in the standard IEC 61851-1.* [17]

Charging mode	Description of properties
Mode 2	• An AC charging mode for "slow charging" of EVs. • Uses a standard household socket or a 3-phase socket. • 1-, 2- or 3-phased charging with current up to 32 A. • With standard household socket the current is limited to around 8 A for safety reasons. • Power around 2 kW. • Charging cable equipped with in-cable control box which enables features such as restriction of charging current and safety features.
Mode 3	• An AC charging method intended for "basic charging" of EVs. • Uses a dedicated EV 3-phase socket. • 1-, 2- or 3-phased charging with current up to 3x63 A or 1x70 A. • Power between 1,4–43 kW. • Charging cable equipped with in-cable control box which enables features such as restriction of charging current and safety features. • Enables implementation of V2G.
Mode 4	• A DC charging method for "fast charging". • Maximum current of 200 A and theoretical maximum power of 120-170 kW. ($\sim$ 50 kW in practice) • Fixed charging cable in the station • Enables control of the charging current.

Charging mode 2 is a slow charging method that is intended to be a secondary charging option or a charging method for the transition period towards the full adoption of EVs. Like mode 3, in charging mode 2 vehicles internal charger is being fed with AC current. However, the charging can be done from a standard household socket and for safety reasons the maximum current is limited to around 8 A reaching charging power of under 2 kW. [16] The charging station is equipped with similar safety functions as mode 3 charging stations.

Charging mode 4 is also referred to as "fast charging". Contrary to modes 2 and 3, mode 4 is DC based charging method that can feed currents up to 200 A and can theoreticly reach power of 120–170 kW even though in practice the charging power is usually limited to around 50 kW. Similarly to the basic charging method, mode 4 enables control over the charging current drawn from the feeding network but the application of V2G is not usually possible. [16] [17]

2.2.3 Impact on distribution system

Charging of EVs will obviously increase electricity demand. However, the most significant consequences in terms of distribution networks will arise due to peak loads caused by simultaneous charging pattern while the energy demand will play a less significant role.

Typically EVs consume around 0,15–0,30 kWh/km of electricity depending on the weight, performance and aerodynamics of the vehicle. Assuming an average consumption of 0,20 kWh/km the electrical energy required by Finnish EV fleet would be 56 MWh in 2020 and 367 MWh in 2030. These calculations have been done based on the adoption rate of EVs presented in Figure 4 and expected development in vehicle mileage [13]. To set these numbers in scale, the total electricity consumption of Finland in 2016 was 85,1 TWh [18] so the expected penetration of 120 000 EVs in 2030 would represent only a 0,4 % increase to the current national electricity consumption. Therefore the increasing number of EVs will most likely not introduce any problems in terms of energy consumption.

However, in terms of peak load the impact of EV penetration can potentially be at least locally problematic. The charging pattern of vehicles is similar between EV owners, meaning usually charging will take place in the early evening as people come home from work. The charging powers are high in order to achieve shorter charging times, which is preferable for vehicle owners. As the charging will also typically take place in residential areas the simultaneous loads can cause stress especially to the lowest topologies of the distribution grid. Without any control over the charging schedule and currents the congestion of LV and MV grid is possible. Too high powers may lead to overheating of grid components which shortens their the life time and causes malfunctions. [19]

Multiple studies show that the effects deriving from the high peak loads will mostly affect distribution transformers. [20] Also, in case of very long and too small dimensioning of LV conductors, it is also possible to have non-negligible voltage drop, line losses or other power quality problems. [19] These phenomenons will be further assessed in sections 2.2.4 and 2.2.5.

EV charging without control over time or current, also referred to as "dumb" charging, can increase the peak load during early evening. With high penetration levels and no control over the charging patterns it is possible that the hourly peak loads can increase to harmful levels in terms of LV and even MV networks. [19] It is however likely, that with further penetration of EVs also smart charging will be adopted, which will enable shifting charging loads to hours of smaller demand. That way the increase in peak load can be avoided and in best case the charging can be used to even out the demand curve. [22] Figure 5 shows how the implementation of smart charging can ideally smoothen the demand fluctuation while avoiding the increase in peak load.

For the vehicle owner however, "dumb" charging can be considered as the most convenient charging method because the car will be operational as soon as possible. As the "dumb" charging can also be considered the most challenging situation in terms of the supplying grid infrastructure, most of the studies assess EV charging

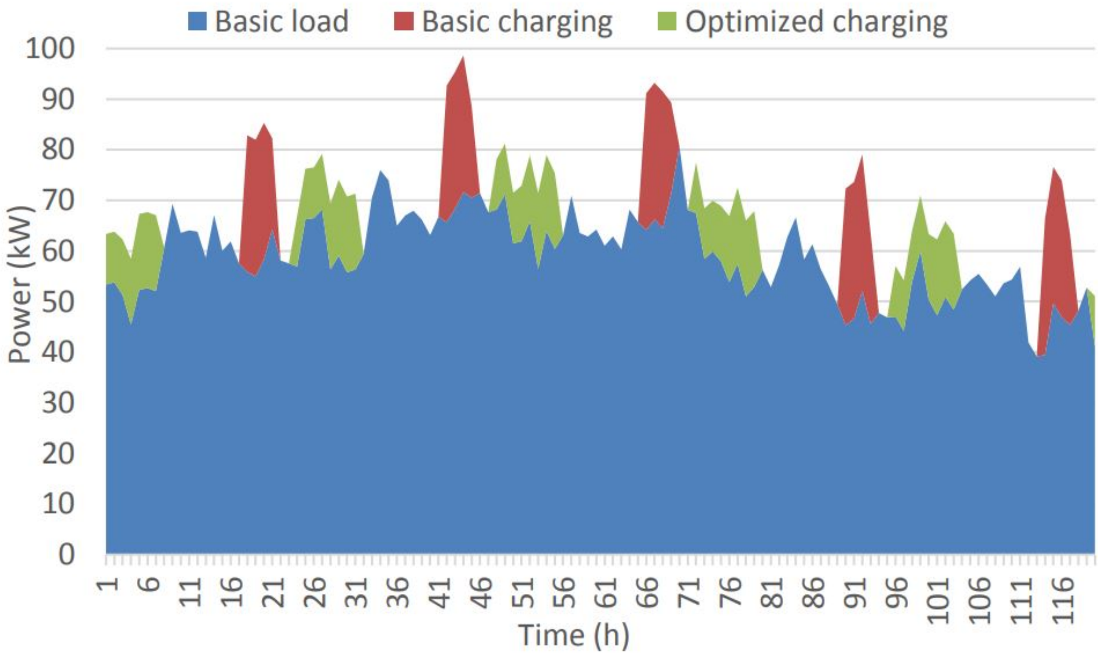

Figure 5: *Effect of "dumb" charging (red) and smart charging (green) on typical residential load (blue).* [21]

impacts in worst case scenario of no smart charging functionalities. If the grid is able to withstand charging without smart control, it will be able to withstand smart charging application too.

2.2.4 Load effects

Most notable effects of EV charging can be seen in distribution transformer peak loads. Results from three different studies about distribution transformer's load changes have been gathered in Figure 6. All of the studies have been conducted as simulations from the point of view of a Finnish distribution network and all studies have assessed the impacts based on worst case scenario of "dumb" charging. Two of the studies evaluate effects of EV charging in actual urban networks of Vantaa [23] and Tampere [24] and one of the simulations evaluates the effects in a typical rural network [20].

Even though all studies more or less agree that the effect on distribution transformers is the most significant impact, the resulting peak loads are mostly in tolerable range even with unrealistically high penetration rates of EVs.

In Vantaa's case the simulations were done with charging powers of 3,7 kW and 11 kW with both 1- and 3-phased charging. In all the cases the achieved increases in distribution transformer loads were negligibly small and the differences between simulation cases were insignificant. However, it was noted that in areas with a lot of electric heating, the increases in peak load were more significant than in other areas, as the additional charging load takes place at the same time with the heating load.

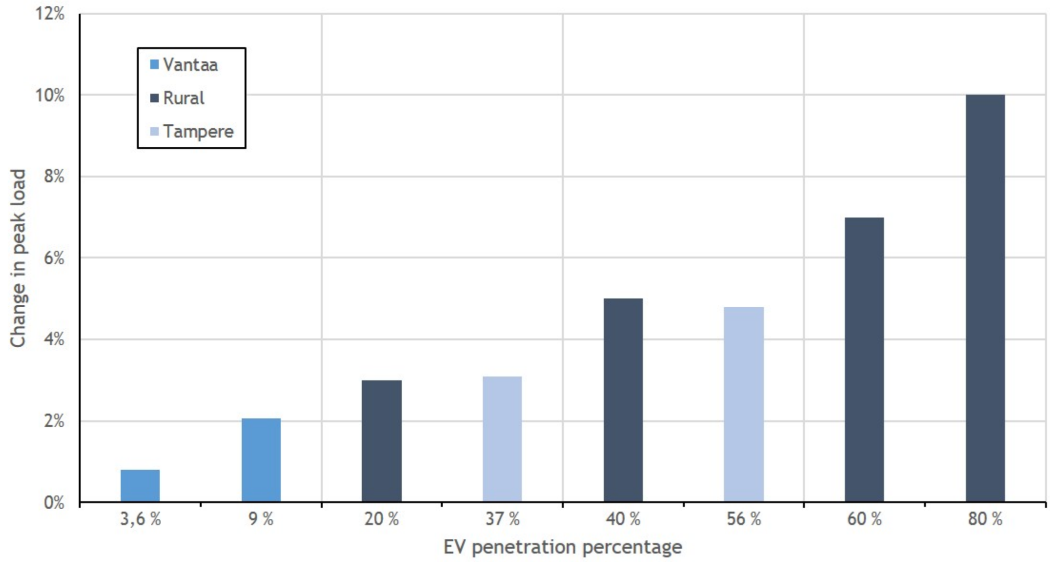

Figure 6: *Summary of three studies evaluating changes in distribution transformer loads as a function of penetration level in urban networks of Vantaa* [23] *and Tampere* [24] *and one typical rural network* [20].

[23]

In a simulation of Tampere's network, it was found that the effect of even high penetration level of EVs will have only a very marginal effect on 110/20 kV main transformers. Furthermore, the effects on MV feeder load levels was also practically negligible with an average increase of 2,4 % and 3,6 % in the two different scenarios. Also, as can be seen from figure 6 the increases in distribution transformer peak loads are relatively small compared to penetration levels. As the distribution transformers are usually slightly over dimensioned in order to ensure operation during back-up connection situation, especially in urban environments it is likely that even the 4,8 % peak load increase of the higher penetration scenario will not cause problems in terms of overloading transformers. [24]

In case of rural network it was found that the effects on transformer load levels might be slightly higher. This is due to the fact that dimensioning of distribution transformers is usually tighter in rural networks. Furthermore, the number of customers per transformer is smaller compared to urban areas, which means that introduction of only few EVs to a specific feeding area has potential to cause higher relative increase in load levels. [20] However, penetration of EVs can be expected to focus on urban areas where the commuting distances are shorter and the charging infrastructure will develop faster. Therefore likelihood of problems in less densely populated areas is low.

In addition to the three studies compared in figure 6, a case study about the distribution network in Jyväskylä has been conducted with slightly different approach to presenting the results. The case study consists of five different penetration level scenarios and similarly to other studies it found that the increasing loads in all scenarios have a very little effect on MV and LV feeder load levels. The study also assessed the proportion of overloaded distribution transformers in all scenarios. Percentages of overloaded transformers with 3 %, 20 %, 55 %, 80 % and 100 % penetration levels were 0 %, 1 %, 6 %, 11 % and 20 %, respectively. [25]

To summarize, even though increases in distribution transformer loads become higher with larger penetration rates, they will unlikely introduce any severe problems to distribution networks. With expected EV penetration of 4,1 % by year 2030 it seems that even without smart charging the effects of EV charging will be within tolerable limits. Even though individual challenges may arise the probability of encountering extensive problems in the grid seems low. Furthermore, with the introduction of smart charging the increases in peak loads will be restricted to much lower levels than presented above.

2.2.5 Power quality

In addition to increases in peak loads, power quality issues can arise due to EV charging. These problems are difficult to generalize, because they are highly dependent on the used charging method, vehicles internal charger design and the configuration and dimensioning of the feeding network. It is shown that power quality impacts such as voltage unbalance, harmonic distortion and flicker may be caused by EV charging. [19] These phenomenons will mainly affect LV network.

Simulation in Tampere's network showed that larger penetration of EVs may cause difficulties in LV network's voltage drop levels. With 37 % and 56 % EV penetration levels the percentages of LV feeders with voltage drops of over 12 % were 5,8 % and 11 % [24]. Probability of too high voltage drops is more evident in rural areas, where the LV feeders tend to be longer. However, the penetration levels assessed in the study are very high and the situations where voltage drop increases over the limiting values are not extensive. Furthermore, due to heavy investments in security of supply in Finnish distribution networks, capacity and robustness of rural network has significantly increased during the last few years. Therefore, the probability of severe problems in terms of voltage drop is not remarkable in the near future.

Other power quality problems of EV charging have been studied less in last few years. Some studies show that phenomenons such as voltage unbalance, flicker and harmonic distortion can theoretically be caused by EV charging. [26] [23] However the situations where the effects become non-negligible are usually unrealistic, such as charging multiple EVs with high powers from same phase of the feeder. [19] In most cases the use of 3-phase charging methods will limit the occurrence of power quality problems. Furthermore, the internal chargers of the vehicles will improve as the technology matures. Overall the power quality problems caused by EV charging might be un-negligible in some limited cases but there is no reason to assume that such phenomenons would cause extensive harm in distribution networks.

2.3 Heat pumps

In this section the assessment of heat pumps (HP) is limited to heating applications meant for residential scale space heating and domestic hot water heating. Large heat pumps designed for industrial, commercial or district heating purposes are left out of the assessment. There are a few different types of heat pumps but essentially the main operation principle of all of them is the same. Heat pump transfers heat from a heat source to a heat sink using refrigeration cycle. Depending on the type of the pump either air, ground, or water can act as a heat source while ambient air of the household or domestic hot water tank acts as a heat sink.

The main motivation behind application of HP systems for domestic heating is the energy efficiency of the heating method. Even though the pump consumes electricity, it is more efficient heating method than for example direct electric heating. Efficiency of a heat pump is described with a coefficient of performance (COP). Because HPs transfer heat instead of converting it, heat pumps can achieve COPs of clearly over 1,0 therefore providing greater amounts of thermal energy than the amount of electrical energy consumed. For example a heat pump with COP=3 can provide a thermal load of 3 kW with only 1 kW of electrical power.

2.3.1 Heat pumps in Finland

According to SULPU by year 2016 there were total of 800 000 heat pumps installed in Finland. HPs are one of the most favored heating systems for new detached houses and annually approximately 60 000 new HPs are installed. Most popular heat pump technologies in Finland are air-air heat pumps (AHP) and ground source heat pumps (GHP). [28] Development in HP penetration rate in Finland is presented in figure 7.

Currently heat pumps produce 7 % of residential heat energy but the amount is expected to increase in the future. [29] Ministry of Economic Affairs and Employment evaluates that the amount of HP systems will keep increasing in all types of residential and commercial buildings. By their estimation HPs will account for 10 % of total heat energy consumption in Finnish building stock by year 2030. [14]

In an study by Gaia Consulting in 2014 it was estimated that by year 2030 there would be 1,7 million operational heat pumps in Finland. This would mean that the penetration of HPs would more than double from the current situation. The study takes into account the current housing stock and the predicted annual construction of new houses as well as the decrease in old housing units. [30] Also old detached houses transitioning from other heating sources, such as oil heating, to heat pumps are of significance. Taken into account the fast adoption rate since 2014, the estimation presented in the study seems entirely possible assuming that the housing construction estimations hold. In two years since 2014 total of 119 000 HPs have been installed [31]. Assuming a steady rate of installations in the future there would be 1,63 million installed heat pumps by year 2030.

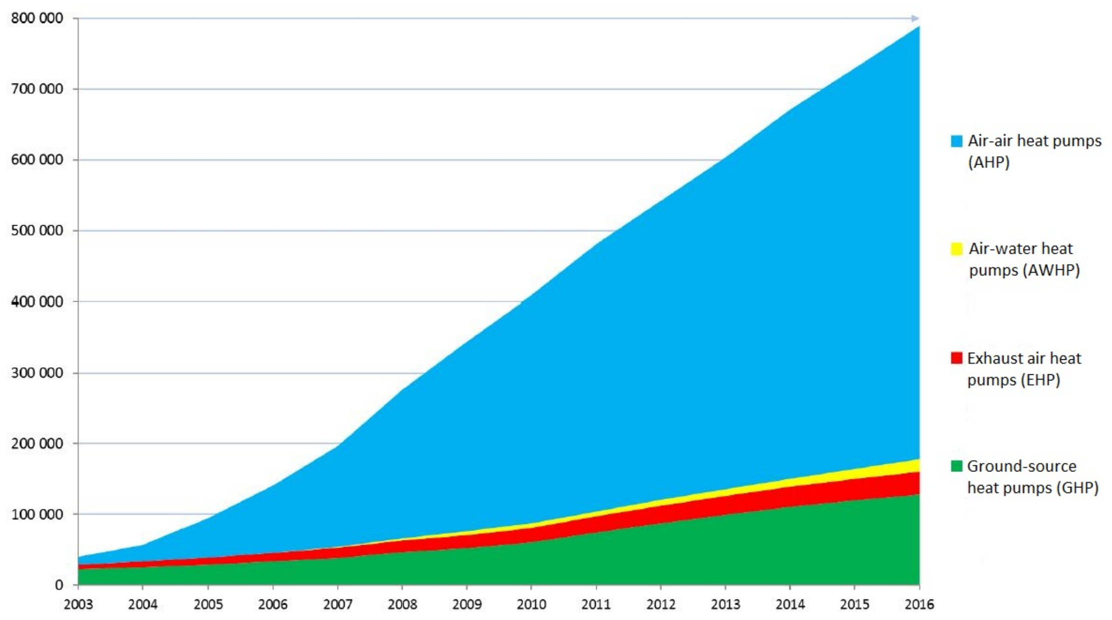

Figure 7: *Quantity of different heat pump technologies in Finland as a function of time.* [28]

2.3.2 Impact on distribution system

Similarly to the impact of electric vehicles, heat pumps have theoretical potential to affect peak energy and power of the distribution system while power quality issues are also possible. Whether the increasing number of HPs will decrease or increase electrical energy and power demand is widely discussed and can vary between countries. In the end the resulting direction is dependent on which heat sources are being displaced and which heat pump systems are being used. The dimensioning of the HP system also has to be taken into account. Systems can be dimensioned to cope with the peak demand of the building, but especially in case of AHPs more common is to dimension the heat pump to cover around 40–60 % of the heat demand [27].

In general it can be stated that if the heat pump is used to substitute electric heating the resulting effect on peak energy and peak power demand will be descending. On the contrary, if other heating systems such as oil heating are being substituted the electrical energy consumption and peak load will increase. Furthermore, installations in new buildings naturally also have increasing effect on energy demand and load.

Typically heat pumps are used to either completely substitute oil heating or reduce the energy consumption of electric heating. [32] As the substitution of oil heating increases peak load and the substitution of electric heating decreases ít, the resulting effect of the HP penetration can be hard to evaluate. Some studies on the subject are however presented in the next subsection.

2.3.3 Load effects

In global research the general opinion is that penetration of heat pumps to space heating sector will substantially increase residential loads. A British case study concludes that heat pumps will introduce significant problems in terms of thermal limits of the LV network. [112] Another study in Netherlands concludes that high penetration rate of heat pumps may cause up to 100 % peak load increase in residential loads. [34] However, this is not necessarily the case in Finland. Significant amount of Finnish detached houses utilize direct or water circulation electric heating systems and replacing them with HPs will have a reducing effect on resulting load levels. Finnish LV and MV networks are already dimensioned to cope with the heavy loads of electric heating during the cold winter months and therefore the resulting effects of heat pumps can not be generalized from studies conducted in other countries.

In a recent study a simulation of heat pumps load effects in Finnish power system was conducted with two different heat pump development scenarios. Study simulated peak loads of a typical coldest week of the year in 2030 focusing solely on detached residential houses, leaving apartment buildings and terraced houses out of the assessment. The study assumed that by year 2030 total of 370 000 existing houses will substitute their heating method with heat pumps. Oil heating and electric water circulation heating will be substituted with ground-source heat pumps and direct electric heating will be supplemented with air-air heat pumps. [35]

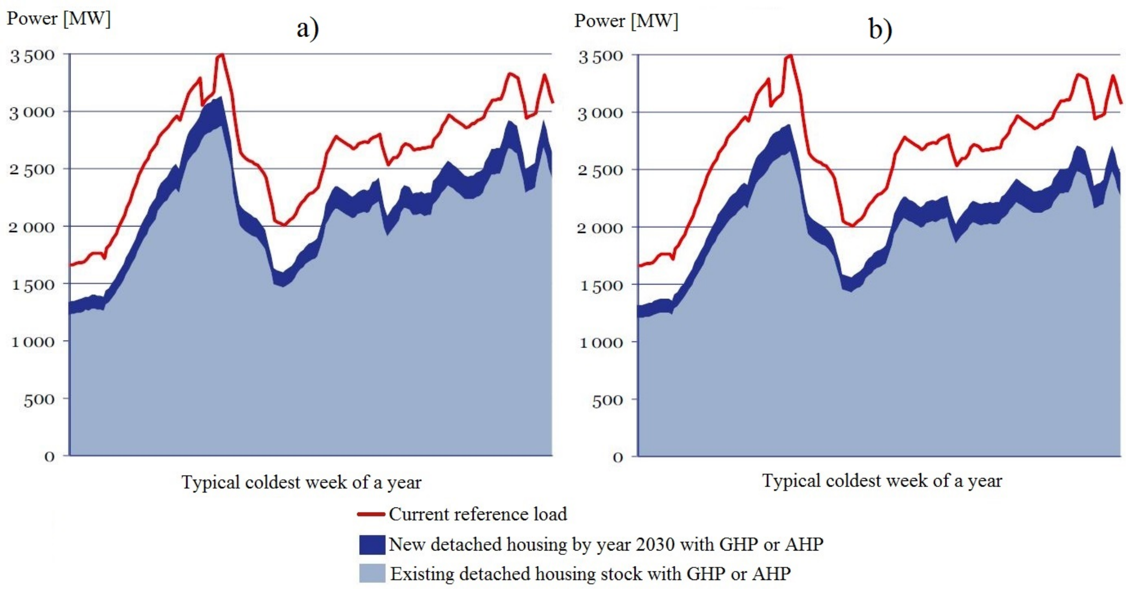

Figure 8: *Load impact of heat pump penetration in detached houses during a typical coldest week of a year. a) "Business as usual" scenario. b) "New technologies" scenario.* [35]

The two different scenarios had different expectations about the development of HP technology. "Business as usual" scenario assumes that no significant development will be made in HP technologies and that the dimensioning of the pump systems will be done as it is currently done. "New technologies" scenario on the other hand assumes that all the GHPs will be dimensiond to fully provide the heating demand of the building and that the COP of the AHP will be slightly better in 2030. [35]

Study found that in both scenarios the penetration of HPs in detached residential houses will have a reducing effect on load levels during a typical coldest week of a year. In "business as usual" scenario -10 % average decrease in load levels can be achieved while in the "New technologies" scenario average decrease of -17 % can be achieved. The load reductions from transitioning electrically heated houses to use heat pumps seems to be larger than the load increase from new houses and converted oil heated houses. Figure 8 presents results of both scenarios. Red line represents the current reference situation, light blue accounts for only the existing buildings when converted to use heat pumps and dark blue represents the new building stock that will be constructed by 2030.

In addition to the simulation results presented in figure 8, an individual assessment about the load level change during the highest realized electricity demand in the 21st century was made. It was found that in terms of currently existing housing stock with HP penetration level of year 2030 the peak load will slightly decrease even during this exceptionally cold day. However, due to new housing that will be built by 2030, the resulting peak load will be slightly higher than in the current reference case. [35] Peak load levels of different scenarios during this demand peak are compared in figure 9.

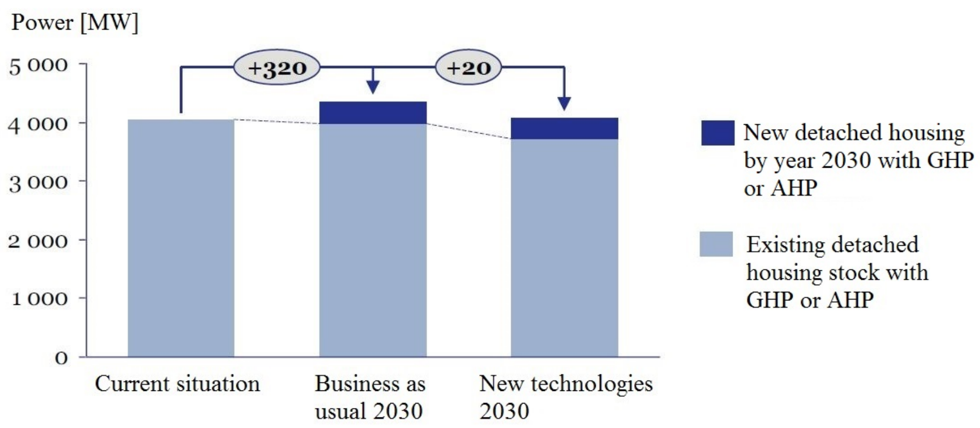

Figure 9: *Impact of heat pumps to residential housing peak load during the highest demand hour of the 21st century (6.1.2003).* [35]

Few other studies also conclude that the load impact of heat pumps will likely not cause extensive problems in terms of Finnish MV and LV networks. [36] [37] In most cases HPs are installed in originally electrically heated houses, in which case the resulting impact to load is decreasing. In the case of new houses the supplying network will have to be individually planned, built and inspected, and therefore possible problems will likely be eliminated.

It seems that heat pumps have a realistic potential of decreasing residential load levels during a typical year. Even in the case of exceptionally high demand the increase in peak load will be due to organic growth of new housing stock. However, the studies are mainly focused on detached houses and application of heat pumps in other housing types might alter the results. As mentioned, the resulting impact of heat pumps to the load levels is highly dependent on, which heating methods it is used to replace. Therefore, if the forecasts about displacement of different heating sources are too optimistic or pessimistic, the resulting load impact can be higher or lower.

2.3.4 Power quality

It is unlikely that integration of heat pumps will cause any significant long term problems in terms of voltage drop or voltage unbalance. Individual problems may arise in specific conditions, but the effects will not be observed systematically throughout the whole network. Highest risk areas are long and tightly dimensioned LV feeders with multiple new heat pump installations substituting heating methods with originally no electrical load. [36] However, investments in security of supply during the last few years have increased the robustness of rural network in Finland, which will reduce the problems encountered in less populated areas too.

Similarly to any electrical equipment with large operating currents, starting of a heat pump may cause flicker or short term voltage unbalance to the supplying LV grid. Flicker is more common with 1-phased AHPs and usually it can be avoided by changing the supplying phase or using 3-phased power supply. [38] Short term voltage unbalance can be encountered in case of both, AHPs and GHPs. However, because GHPs usually require larger powers, they also produce larger voltage volatilities. In modern heat pumps however, the power quality issues are prevented with a slow start functionality that allows the pump to slowly increase the power drawn from the grid until it reaches maximum load. [39] Without slow start it is possible to produce current peaks high enough to be detected by overcurrent protection devices.

2.4 Electrical energy storage

Generally there are multiple different types of electrical energy storages (EES), that are suitable for different applications in variable sizes and time scales. In this thesis the assessment is focused on residential scale electrical energy storage owned by individual customers, installed in residential LV network behind the AMR meter.

Electrical energy storage as a definition is a storage technology that is able to store electricity which it can later release. Therefore, for example domestic hot-water boilers which are currently a popular energy storage method in Finland, are ruled out from the assessment. In practice the assessed storage technologies suitable for purposes described above consist of battery technologies. Most common battery technologies in consumer use are Lead-acid batteries and Lithium-ion (Li-ion) batteries. Lead acid batteries are the battery technology of traditional gasoline fueled cars, while modern EVs usually rely on Li-ion batteries. In domestic EES applications lead acid batteries are currently the most popular choice but it is likely that Li-ion batteries will generalize in the future.

2.4.1 Properties of battery energy storages

Battery technologies are practically the only electricity storage feasible for residential use. The prices of battery energy systems vary between different technologies and currently lead-acid batteries are the most feasible choice for residential customer. The prices of Li-ion batteries are however expected to decrease due to the huge increases in manufacturing volumes mostly because of electric vehicles. [40]

Battery storages are usually specified as a medium discharge time energy storage. Storing times suitable for batteries depend on the technologies used, but generally they can be used for applications requiring storage from seconds to multiple hours or even days. [41] Seasonal storage applications with battery technologies are not currently feasible. Batteries can be tailored to specific applications and therefore they are a flexible EES method in their operational area. Discharge of large powers over small time periods, as well as small powers over long periods are both possible. [40] Comparison of different EES technologies in terms of rated power, energy, and discharge times are presented in figure 10.

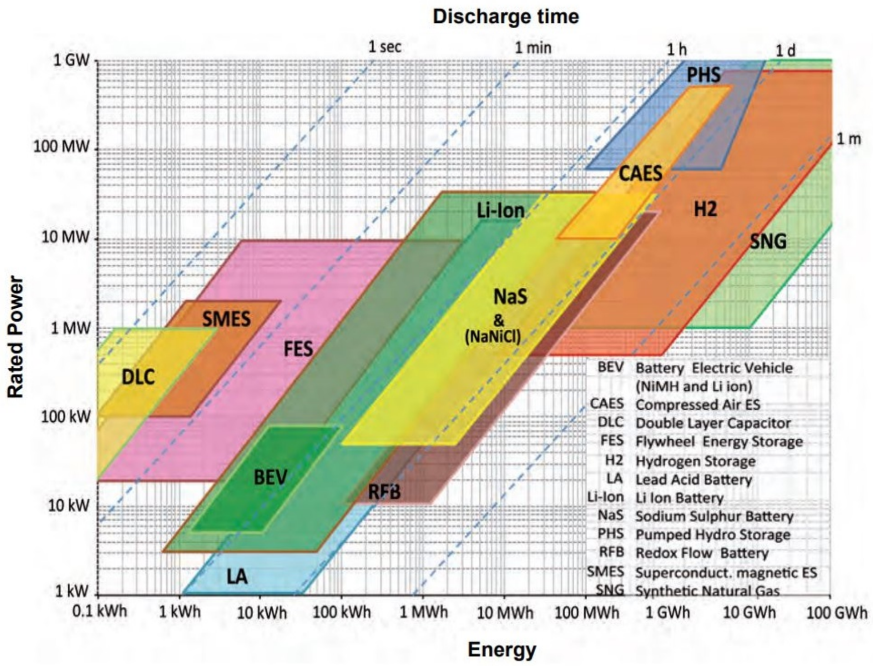

Figure 10: *Comparison of different EES technologies in terms of discharge time, energy and rated power.* [40]

2.4.2 Application of domestic battery storage

Electrical energy storages are believed to be an important part of electricity grid infrastructure in the future. They have been said to be an enabling technology for the introduction of smart grid. [40] Large scale or aggregated small scale EES will play a a critical role in integration of renewable energy sources to the energy system and in implementation of demand response. These functionalities are motivated by the needs of the utilities operating the electricity system and will be further assessed in section and 2.6.

This section focuses on application of EES in customer's network with motivation for achieving personal gain or benefit from the customers point of view. Ruling out the demand response applications of residential EES systems, there remains two main use cases for residential battery storage systems [21]:

- Optimizing use of personal micro generation
- Peak load shaving in order to reduce electricity costs

This section focuses on assessing these two different usecases for EES applications. However, a battery storage can also operate as an UPS or emergency power supply in case the customer has appliances that need continuity of supply. [40]

The most common use case of residential EES is integration of battery storage as a part of personal micro generation system. [42] In practice these systems are residential solar energy systems installed on the rooftops of detached houses. The main motivation of utilizing battery energy storage as a part of a PV system is to optimize the use of self produced energy to match customers own demand. As the solar energy production peaks during mid day while the demand is low, battery storage enables the customer to store the excess energy produced during the day to be used later in the evening when the consumption of electricity peaks. By utilizing EES integrated with PV generation it is possible to reduce the amount of electricity purchased from the grid and therefore gain savings in electricity costs. Even though it is possible to feed produced excess energy to the grid, it is economically much more feasible to consume the electricity personally. [43]

Using EES system for peak shaving of residential loads can also be justified by economical gain of the customer. In the case of peak shaving the battery storage is charged during hours of low demand, when the price of electricity is low and then later discharged to personal use during the hours of high demand, when the electricity price is at its high. In order to gain economical benefit from peak shaving, an hourly tariff for electricity needs to be in use. Additionally, the possible introduction of power based distribution tariff might further encourage the penetration of battery energy storages for personal peak shaving purposes.

It is unlikely that storage systems will be acquired solely for emergency power supply purposes. However, it is possible to use EES as a backup power source during the blackouts even though the primary purpose of the battery storage is something else. Furthermore, combination of different use cases in EES operation is possible. The principle of using electrical energy storage for peak shaving and PV optimization is demonstrated in figure 11.

Currently the amount of battery energy storages in Finland is practically negligible [21] and predictions about their future adoption rate are hard to find. However, annual installations of new solar energy systems to residential and commercial buildings have increased and therefore the amount of ESS capacity can be expected to increase too, even though not nearly all PV systems utilize storage. Also, the further adoption of

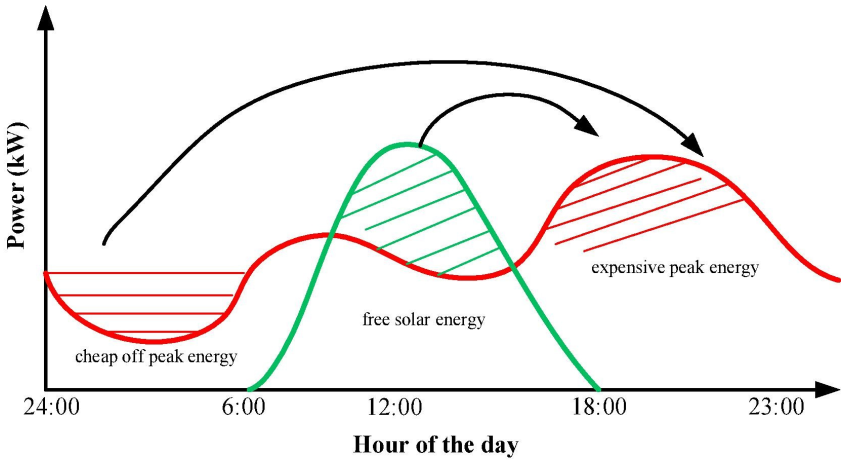

Figure 11: *Principle of using electrical energy storage for peak shaving and solar energy production optimization.* [43]

electric vehicles will probably affect the penetration of residential battery storage systems. It has been shown that the utilization of EVs internal batteries to similar functionalities as separate ESS systems is possible [44].

2.4.3 Grid impact of EES

Grid impacts of electrical energy storages are difficult to pinpoint precisely, as the impact is highly dependent on the way the battery storage is being used. It is however likely that the resulting effects from peak cutting and micro generation integration operations resemble each other and at least in theory both use cases should have a reducing effect on peak load demand. In both cases the energy stored in battery storage is ideally used during high demand of electricity, therefore reducing the electricity demand during daily load peaks.

Peak shaving motivated by the customers personal will to optimize electricity costs can have a minor effect on local peak load levels. As the battery storage is being charged during the hours of low demand and discharged during high demand, the load variations will be slightly smoothened. However, due to high prizes of EES systems, the dimensioning of battery storages usually result in relatively minor effects. A simulation in Finnish distribution network concludes that customer peak shaving will decrease the maximum load of a year by approximately 3 % [21]. Figure 12 presents results of the simulation.

It has been shown that utilization of battery storage with residential solar micro generation can in fact reduce load volatility caused by small scale PV generation. Volume of the reducing effect is determined by the dimensioning of the battery storage compared to the nominal power of the PV system. However, it seems that the resulting effect of energy storage is not enough to significantly reduce the load variations from micro generation but it is possible to prevent or significantly reduce the amount of excess electricity being fed into the distribution system from customer's micro generation [45] [21]. The effects of solar micro generation on load patterns are

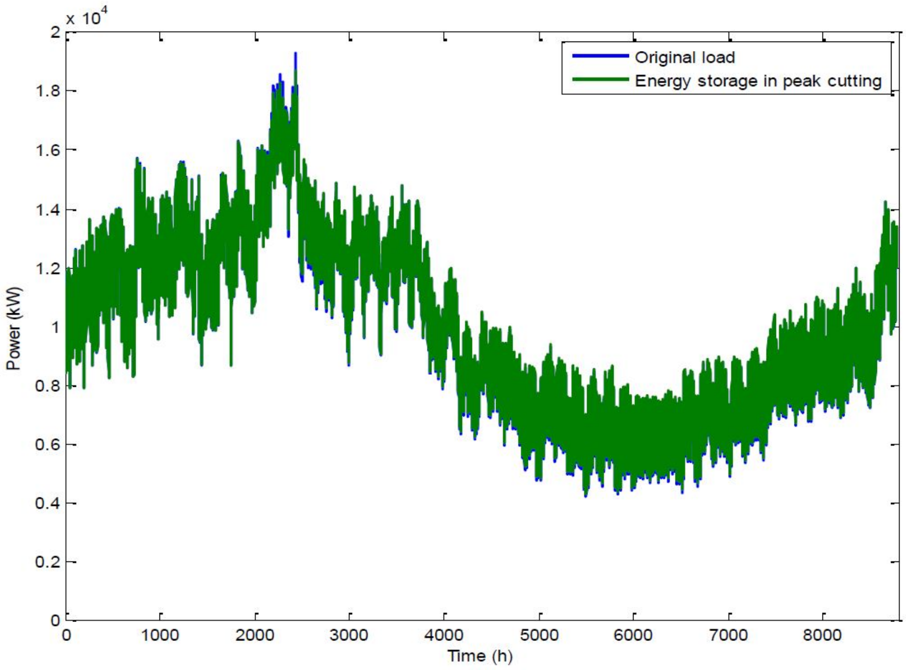

Figure 12: *Effect of residential peak shaving to the load curve of an average year.* [21]

discussed in more detail in section 2.5.

The assessment of battery storage operation purely meant for one purpose might not be realistic. In reality the storage system will most likely be combined to the use of both scenarios presented in this section, which will have effect on the overall impact of the system. Also, the application of domestic battery storages to demand response purposes as aggregated virtual power stations will be a more significant factor in terms of distribution system.

2.5 Microgeneration

This section is focused mainly on small scale photovoltaic (PV) electricity generation. Large wind farms and utility scale solar power plants are left out of the assessment. Solar panels are the most popular micro generation method and especially the installation of PV panels to residential houses' rooftops has gained popularity during the 21st century. In terms of especially LV network and distribution transformers, municipal electricity generation can be assumed to have the most significant impact.

Generally microgeneration is defined as generation of under 100 kVA nominal power. [46] However, typical PV systems installed in detached houses are dimensioned to generate powers between 2–8 kW. [47] [48] In national scale solar power is very marginal and practically negligible in terms of yearly electrical energy generation. In residential scale PV systems can however be economically feasible. The main motivation behind personal PV generation is to generate electricity for personal use, therefore reducing electricity costs.

2.5.1 PV adoption in Finland

Even though solar energy is marginal in terms of national electrical energy generation, the penetration of municipal microgeneration has accelerated fast during the last few years. Reliable statistics about quantity of grid connected solar energy systems in Finnish network has only been gathered from from 2015 onward. According to Finnish Energy Authority there was total of 25 MW of PV generation connected to the grid at the end of year 2016, including PV systems with nominal powers over 100 kVA. In 2015 grid connected PV capacity was 8 MW which means that the amount more than tripled in one year. [49]

Respectively, the solar power capacity growth connected to the network of the DSO in question has accelerated during year 2017. Currently (17.10.2017) there are total of 2144 PV generation systems connected to Caruna's distribution grid resulting to a total nominal power of 14,1 MW which is more solar power than in any other DSO's network in Finland. Only 11 solar energy systems are larger than 100 kVA and respectively, account for 15 % (2,1 MW) of the solar energy capacity in the grid. Microgeneration on the other hand accounts for 85 % (12,0 MW) of the nominal solar generation power in the grid. Approximately 90 % of grid connected PV systems are installed in residential buildings. Integrated capacity of solar energy and number of new PV systems in Caruna's network over the last few years can be seen in figure 13.

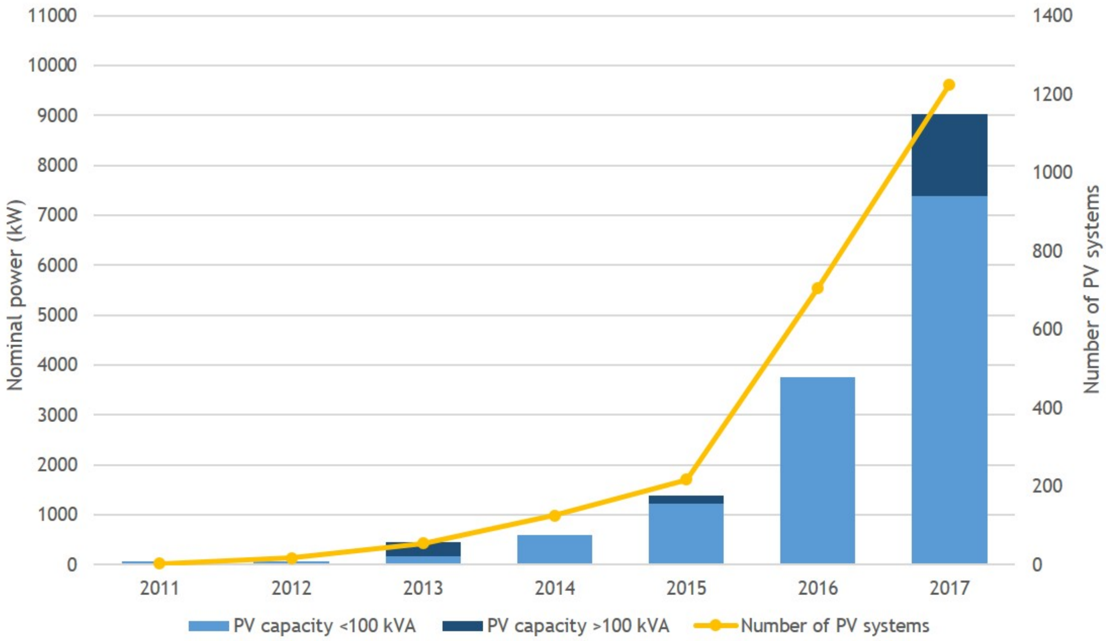

Figure 13: *Annual capacity and quantity of new PV power systems integrated into Caruna's distribution network.*

Globally solar energy production is expected to become a significant electricity generation source and about 30 % of global electricity supply is expected to be generated with solar PV systems. [50] As figure 13 shows, the trend in PV system adoption is clearly positive and the amount of new PV systems has more than doubled during the last few years. Nevertheless, the future national solar energy production quantities are very hard to predict and the evaluation of the subject is mainly based on calculations of technical potentials in Finland. Nation wide predictions about the penetration of solar energy production might not even be realistic due to the very different irradiation circumstances in the country. The conditions for solar energy production are much more feasible in the southern Finland than in Lapland [48]. Furthermore, an obstructing factor for high level penetration of solar power into Finnish power system are the poor solar power generation conditions during winter, when the electricity demand is at its peak.

In a study by Gaia Consulting a theoretical maximum for roof installed PV production in Finland has been calculated. Study took into account the applicable roof area in different type of buildings throughout Finland and calculated the maximum potential of solar electricity production in the case when every suitable roof is utilized for solar energy generation. According to the study, in 2012 the maximum nominal capacity of PV systems in Finland was 11,8 GWp and the corresponding annual energy production 9–10 TWh which represents 10–12 % of the annual electricity consumption in Finland. Respectively, in 2030 the maximum solar electricity generation capacity would be 18,8 GWp corresponding annual electricity production of 15,1 TWh. Solar energy potential increases over the years due to new building construction. [48] However, these estimations represent the theoretical maximum for Finnish solar electricity production and are therefore much larger than the future realized solar electricity production will be. Furthermore, this estimation is done as a nationwide calculation and as already mentioned the areal variations in realistic solar energy potentials are large.

In a study by Sorsanen the realistic solar energy potential in Tapiola district, in Southern Finland was estimated. Again, the estimation was based on calculation of potential solar energy production roof space of the buildings in the area. Study concludes that the realistic solar electricity potential in Tapiola district is 44 GWh/a assuming a full penetration of PV panels to applicable roof areas. This represents 15,6 % of the annual electricity consumption in the area. [51] Results are well aligned with the nationwide estimations by VTT. Solar energy production potential achieved in Tapiola district in southern Finland is larger than national average because solar irradiance is stronger and habitant and building densities are larger.

Because of the limitations of theoretical potential, solar electricity production will never be the main source of electricity in Finnish energy system but there is still much room to grow. In a publication by VTT the techno-economical potential of solar energy production in Finland was assessed. With the assumption that similar feed-in tariffs as in Germany would be introduced, the PV capacity with population of 5,45 million inhabitants would be 2,169 GWp. [52] Assuming that in Nordic conditions 1 kWp produces annually approximately 800 kWh of electricity [53] the respective annual solar energy production would be 1,74 TWh. Similarly Finnish Ministry of Economic Affairs and Employment estimates that the amount of annual solar electricity production in 2030 will be under 1 TWh. [14] Furthermore, a report by Gaia Consulting estimates that amount of solar PV generation by year 2025 will be 600–700 GWh/a with approximately 150 000 PV systems installed. [48]

In respect to these estimations solar electricity will account for only 1–2 % of the annual electricity demand in Finland, assuming no radical changes in electricity consumption. Comparison of the estimations to the current solar electricity production can be seen in figure 14.

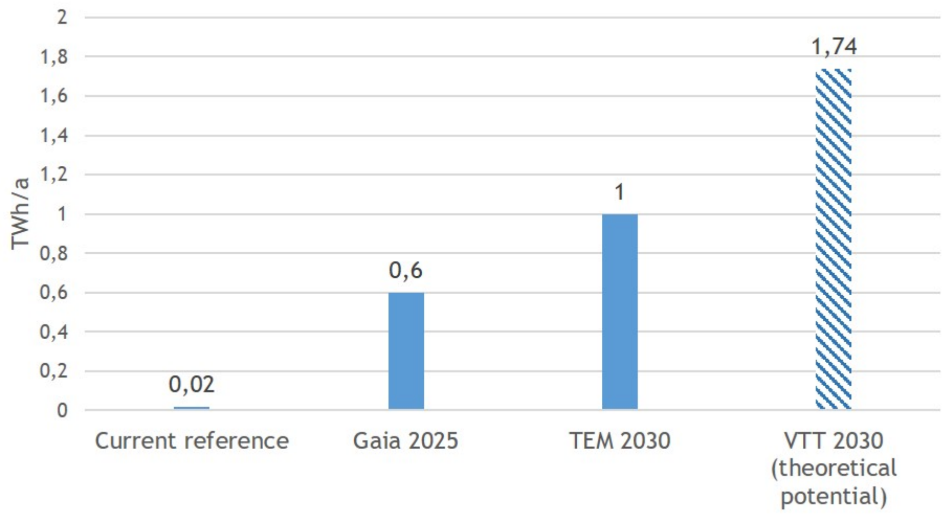

Figure 14: *Comparison of current solar energy production and estimations of the penetration by VTT, Gaia Consulting and Finnish Ministry of Economic Affairs and Employment.*

2.5.2 Impact on distribution system

It is evident that more and more distributed microgeneration, especially solar PV production will be connected to distribution grid in the future. As the production of energy sources such as wind and solar can not be controlled, but it rather depends on weather, matching supply and demand will be harder. Production pattern of roof mounted solar energy system can differ strongly from the consumption pattern of the building, therefore leading to situation where the excess energy that can not be self consumed needs to be fed into the distribution network.

Distribution networks are originally designed for "top-to-bottom" operation where electricity is only being fed from large generation facilities through transmission lines down to distribution networks and eventually to the customer. Distribution system is not designed for power flows in opposite direction and therefore high penetration of microgeneration may impact power quality in the network and cause overloading in network components. In Nordic conditions problems arise especially during sunny summer mid-days when the solar energy production is high and the electricity demand is low. [54]

In terms of whole power system the volatile nature of distributed generation is the most significant impact and problems with stability of the whole system may arise. With decreasing number of large spinning load, angle stability, voltage stability and frequency stability can suffer. [55] Germany is a good example of effects that integration of large amounts of distributed generation can cause. High penetration of wind and solar power in Germany's power system has occasionally led to situations where surplus solar and wind generation result to negative electricity prices. [56]

In respect to distribution network, overloading of the grid components is one of the most significant impacts. However, many other impacts derive from the changing load patterns and reverse power flow. For example problems with network protection, voltage levels and flicker, reactive power management may be detected. Harmonic distortion and increases in fault currents have also been associated with microgeneration.

2.5.3 Load effects

Installation of microgeneration in customer network has an overall reducing effect on the energy demand of the customer, as part of the electricity otherwise bought from the distribution network can be self generated. Volatile and unpredictable microgeneration can cause large volatility to the load levels of the network. As mentioned, especially during summer months of low electricity demand and high solar energy production the direction of the power flow in distribution network can reverse and electricity will flow from customers microgeneration system to the distribution grid. The phenomenon gets stronger with larger penetrations of distributed generation.

The probability and severity of possible effects of reverse power flows in Finnish networks has been studied relatively comprehensively. A simulation study by Tuunanen assessed the effects of 5 kW PV systems in Finnish case network. Case area consists of a single primary substation area with total of nine MV feeders. There is 456 km of MV network and 793 km of LV network with 469 distribution transformers and total of 5624 connection points. Customer density is 164 m/customer, meaning the assessed area is relatively rural. Simulation assumes that approximately 25 % of the end customers in the are to own PV systems. [21]

Results of the simulation show that in annual scale the PV production practically affects the load levels during summer months only. Results presented in figure 15 show that in terms of distribution network load levels the effect of PV penetration is practically negligible during cold winter months, therefore making it very unlikely that distributed PV generation will have any effect on annual peak load level. However, PV generation has clearly a reducing effect on primary substation load levels during sumer months.

Outcome of the same simulation is presented in figure 16 in timescale of one week in July, when solar electricity production is at its highest. Figure shows clearly, how the self use of solar electricity reduces network load during mid day and causes large volatility to the load pattern. It can also be seen that the load becomes slightly negative during Sunday mid-day. However, resulting reverse power flows are still moderate. On the other hand, the large variations in load levels are still problematic for the whole power system and it has to be taken into account that the simulation

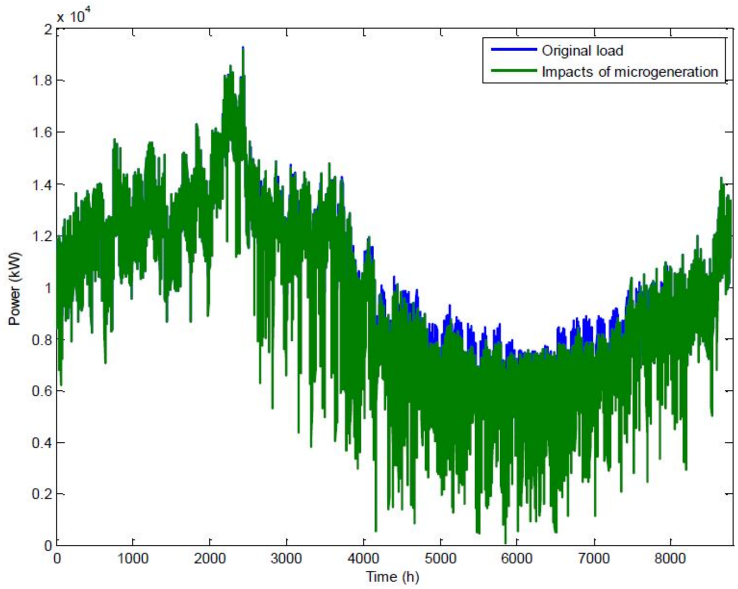

Figure 15: *Annual load effect of microgeneration (green) compared to original load (blue) in simulation of a case network.* [21]

only presumed PV systems to be installed in 25 % of the buildings.

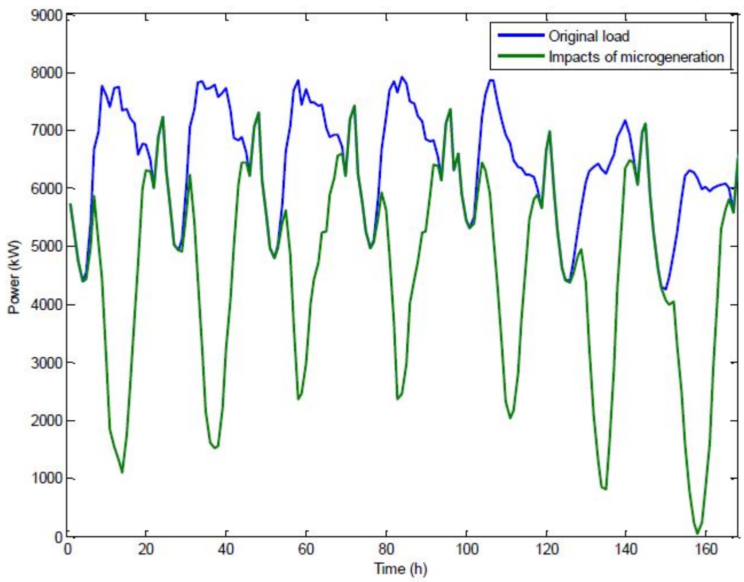

Figure 16: *Load effect of microgeneration (green) compared to original load (blue) in simulation of a case network during one week in July.* [21]

In an other study the housing potential of roof mounted PV installations and their effect to load levels of case network was studied. The case area in question consists of rural and urban network and reflects pretty well the average of Finnish DSOs in terms of peak power and annual energy delivery. Goal of the study was to determine the housing capacity for roof mounted PV energy production in Finnish distribution network and to determine severity of the effects caused by bi-directional power flow. Study evaluates limits for two cases: one with only residential rooftops utilized for PV and one with all available roof space within 200 m of customer connection points are used. [57]

It was found that overall the situation is surprisingly good especially in the case of only the residential roof area being used for solar PV production. This is largely to do with the fact that Finnish distribution network is originally robust because of the large electrical heating loads during winter. Study shows that in terms of current customer fuse sizes and low voltage feeder thermal limits, the effects of residential PV generation are not very acute. In the case of only residential roof mounting of PV panels nearly 100 % of the customer connections are unaffected and even in the high penetration case only 20 % of the customers need to restrict their production or update their fuse size. In terms of LV feeder thermal limits neither case introduces significant problems. [57]

In terms of distribution transformers and primary transformers the thermal impact with two different PV penetration scenarios are much more significant. Figure 17 a) shows the effect of two PV penetration cases to distribution transformers and 17 b) the effect on primary transformers of the case network. It can be seen that the case of higher PV penetration can have a significant impact on the thermal limits of primary and secondary transformers. [57]

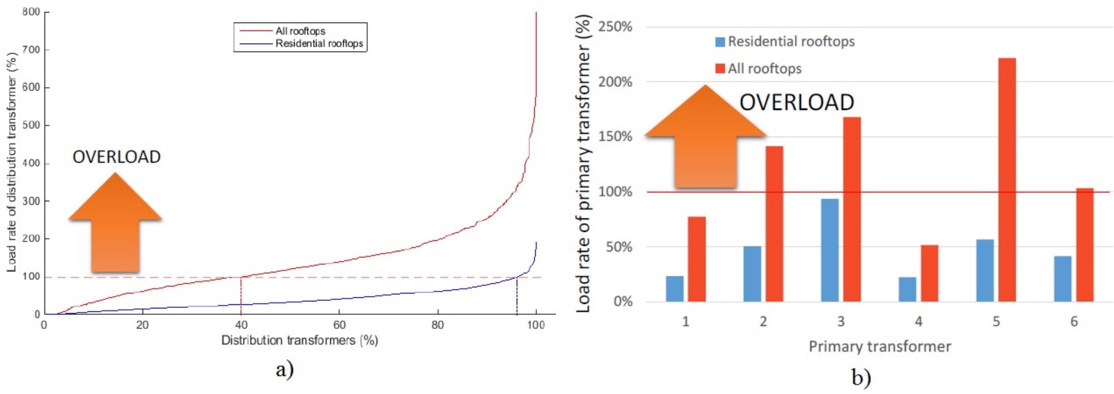

Figure 17: *Impact of PV generation scenarios on load rates of a) distribution transformers and b) primary transformers.* [57]

However, the scenario of PV panels being installed on all applicable roof surfaces in the vicinity of the customer connection point can be considered to be unrealistic compared to scenario with PV panels installed only on residential buildings' rooftops. Furthermore, at the point where PV generation in the extent of the simulations here will be installed, it is likely that the application of residential battery storages and EVs will be noticeable. That will enable a smoother integration of PV production to the distribution system and increase the self use limit of microgeneration.

2.5.4 Power quality

In addition to overloading and thermal limitations of network components, also power quality problems may occur. For example during high PV production hours with low self-use rate the voltage levels of the network can rise as the excess energy is being fed to the grid from the customer connection points. However, from the DSOs standpoint over voltages can be avoided by adjusting the busbar voltage of the primary transformer. Figure 18 shows how lowering busbar voltage from 20,7 kV to 20,0 kV decreases the amount of LV line sections in over voltage. [57] This indicates that it is possible to control LV network over voltage levels by adjusting the primary transformer ratio. However, controlling LV network voltage levels from primary substations would require the distribution of PV generation to be constant throughout the whole feeding area, which most likely will not be the case. Because of the unbalanced distribution of microgeneration to different distribution transformer feeding areas, the use of tap changers in distribution transformers might seem beneficial. However, according to Rauma, controlling voltage at secondary substation level is less effective compared to the busbar control in primary substation level [58].

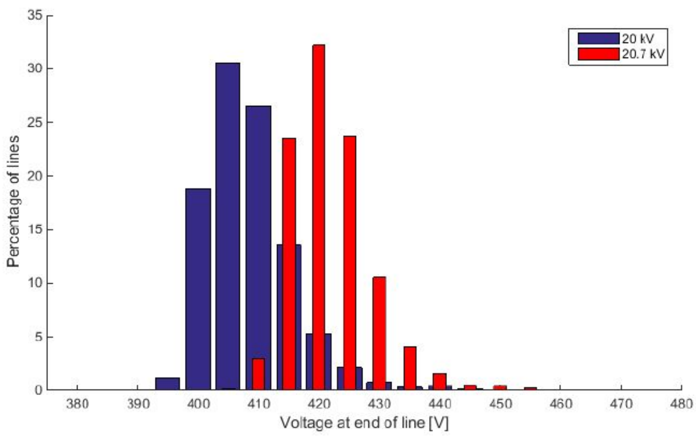

Figure 18: *LV network voltage levels with primary substation busbar voltages of 20,0 kV and 20,7 kV while only residential rooftops are mounted with PV generation.* [57]

Adjustment of voltage level could also be executed by adjusting the power factor of microgeneration facilities in their connection points to distribution grid. However, the significance of a single PV system is negligible in terms of the whole network and therefore the adjustment would have to be systematically generalized to all microgeneration stations. [59] Aggregated control of distributed residential PV productions would however, up to some point, enable voltage level control in small areas of the network.

Distributed microgeneration can also cause problems in network protection. Commonly distinguished problems are: island mode operation, unnecessary disconnection of a power plant or a feeder, delayed short-circuit protection and failure of high-speed automatic reclosing. Most of the problems derive from the fact that originally network protection has been designed to function with only one direction of power flow. [60]

With increasing number of microgeneration it is possible that short-circuit currents rise to level that is harmful for network components. It is essential that PV systems are equipped with disconnectors that provide selectivity to the protection system so that for example island mode operation situations do not occur or that automatic high-speed reclosings do not fail because of the delay in disconnecting microgeneration from the network. It is also possible that with microgeneration the fault current at the busbar of the feeding area is decreased so much that overcurrent protection slows down or becomes completely blind to the fault.

2.6 Demand response

Demand response aims to increase flexibility of electricity demand in order to maintain equilibrium of supply and demand or to level the load variations in the power system. Traditionally it has been possible match demand and supply by adjusting generation of large thermal power plants, but with increasing amount of weather dependent and uncontrollable generation flexibility at demand side of the system is required. During national load peaks the price of electricity usually increases and with application of DR some of the consumption can be shifted to hours of smaller demand. In addition to hourly power balance, demand side flexibility can be used for other ancillary services too.

At the moment the practices and details of demand response are not yet fully shaped and therefore, details and possible consequences of the concept are unknown. DR includes a large variety of different functionalities which have different meanings, motives and earnings principles for different stakeholders. Demand response can for example be indirect influencing to customers behavior with pricing structure or it can be direct controlling of customer loads according to energy price fluctuations. [61] One of the simplest models for demand response is the introduction of Spot-price based hourly energy pricing, which will encourage customers to shift their consumption from load peaks to hours of lower demand. Additionally, DR can be based on needs of transmission or distribution companies' needs for reducing network congestion or acting as a power reserve. As the concept of demand response has not yet been properly introduced to the power system, the details of how it will be realized and what its resulting impacts to different stake holders will be, are not yet certain. [62] Motivation and benefits of demand response from the perspective of different stakeholders are presented in figure 19.

Individual customer loads are usually too small to have an impact in the scale of whole power system. Therefore, the distributed loads (and microgeneration) are aggregated together in order to form a virtual power plants which are able to participate in ancillary service markets. [61] From customer's perspective this may mean handing over control of some electrical appliances to an external party acting as an aggregator. Appliances with largest potential for DR applications are electrical heating and domestic hot water during the winter season. In large buildings also other loads such as air conditioning and lighting can be feasible for DR purposes. [62] Furthermore, especially in the future also microgeneration, domestic electrical

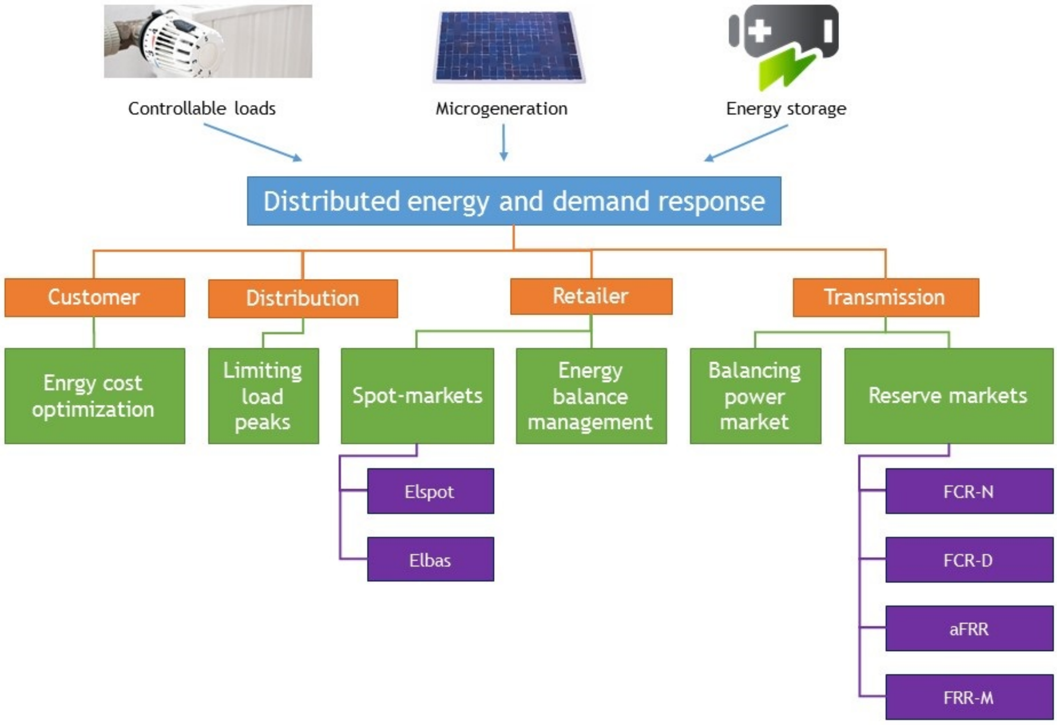

Figure 19: *Motivation for demand response from the point of view of different stakeholders.* [62]

storage and EV batteries can be utilized for DR purposes.

2.6.1 Application of DR in Finland

As mentioned, DR is still an emerging system and all the details of its operation have not yet been determined. However, some estimations about the potential of controllable loads in Finland have been made. Finland has a good starting point for application of DR because of a nearly 100 % penetration of AMR meters in customer connection points. AMR meters have enabled energy balance management based on realized consumption and they also enable the introduction of new hourly based pricing models for electricity retail and distribution.

In theory, AMR meters already provide possibility to control customer loads according to day-ahead market (Elspot). This can be done using time-based control relay that is already being used in the night time off-peak electricity control. However, even tough current legislation requires all AMR meters to include a load control relay, it is not mandatory to connect any loads to it. Therefore in many cases there are no loads connected to the relay. Possibility to connect loads to the relay in the future is not necessarily taken into account in residential network construction and connection of controllable loads to the relay would require renovation of the wiring inside the real estate. Additionally, participation to intra-day market (Elbas) is a little more complicated compared to the day-ahead market, due to technical limitations. For example, faster and more reliable communication links are needed in order to achieve a quicker response. Further more, the participation to markets of fast reserves is unlikely with the current generation of meters due to same reasons. [62] However, the current stock of AMR meters is reaching the end of their lifespan and new generation of AMR meters will be installed. Requirements of demand response can therefore be taken into account in the new generation of AMR meters. Operation of AMR meter management system is assessed more closely in section 4.2.

There are already over 1000 MW of controllable load connected to AMR meters time based relay, which could be utilized for DR applications. [63] Taking into account other residential loads that are not currently connected to time-based control relays, the potential reserve is much larger and it is probable that for example increasing penetration of building automation systems will further increase the amount of controllable reserves. [62] However such operation is still under development and the utilization of these load reserves to DR applications would require a platform that enables the control over the loads and a seamless information flow between different parties.

However, successful execution of demand response is not dependent on the future generation of AMR meters and it is likely that in the future the role of building automation will be significant. Modern wireless automation systems have potential to enable a higher level of flexibility and control than AMR meters. In the case of AMR meters the achieved control is relatively clumsy and controllable loads are mostly limited to large appliances, as mentioned above. With adoption of commercial smart building automation systems the level of controllability can be improved and basically the whole electricity consumption of the building can be adjusted.

Currently biggest barriers for penetration of DR to the power system are more concerned with political and economical factors than with technical limitations. [62] For example, benefits from the participation should be clear to all parties and especially end customer needs to achieve some sort of tangible gain for participating into the system. Participation of customers can be seen as a crucial enabler of successful application of demand response and it is possible that the economical benefit that a single customers achieves from participating in single market signal driven demand response system is so small that for many customers it will be practically negligible [64]. Furthermore, it is possible that the achieved benefits will be cancelled out by changes in distribution costs. There are also open questions in terms of regulation. For example operation of an independent aggregator can mix up the energy balance management of electricity retailers when the realized and forecasted energy consumptions do not match.

2.6.2 Impact on distribution system

As the underlying idea behind demand response is to alter traditional consumption patterns in order to achieve benefits to different power system actors, the resulting impact in distribution networks is naturally mostly seen as load effects. Impacts to power quality are hard to allocate on DR because of the abstract nature of the subject. Whether the effects of DR are positive or negative from DSO's point of view is still uncertain and depends on the execution of the DR system. However, essentially DSO and electricity retailer have a natural conflict of interests in the execution of demand response system. It has been shown that Spot-price based customer load control, which would benefit retailer, has the potential to substantially increase distribution network load levels [65].

When loads are controlled indirectly according to a unified signal such as Spot-price, the loads will be focused to the most optimal time from the customer's point of view. Some of the loads however are not entirely controllable and the timing of the load can be delayed but eventually the load has to be connected. Electric heating and industrial refrigeration systems are examples of loads that can not be delayed indefinitely. This leads to the stacking of loads which can be detected as high load levels during the traditional off-peak times. Furthermore, with incentive to shift consumption to off peak hours it is possible that large load peaks can be observed at the beginning of cheaper hours, as for example electric heating is simultaneously turned on in multiple connection points. This can also increase the short term volatility of the load levels. [62]

Figure 20 presents results of Spot-price driven demand response system to the load levels at primary substation level. Network area under assessment is a mixture of urban and rural distribution grid, which represents average Finnish distribution network fairly well. Loads that are being controlled in the simulation comprise from direct electric heating loads.

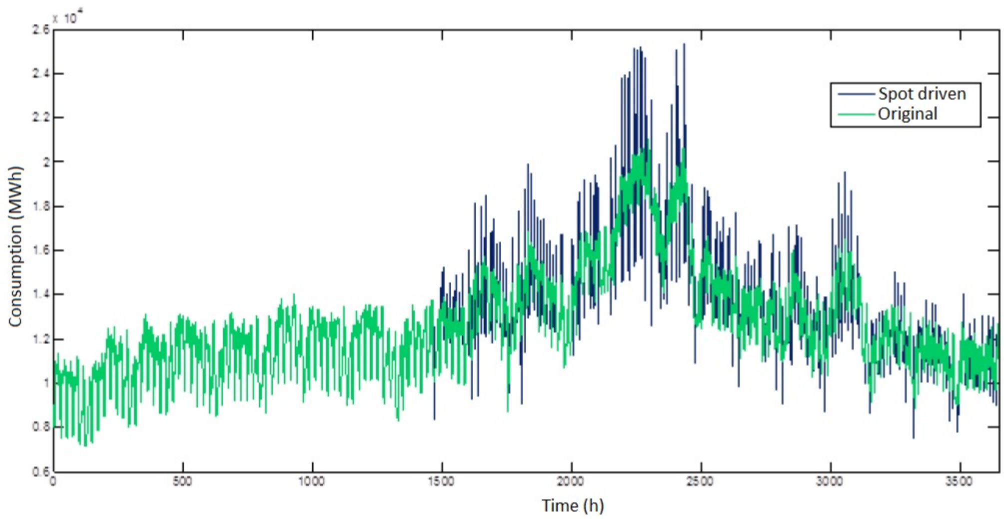

Figure 20: *Impact of Spot-price driven load control on primary substation load levels during first three months of a year.* [62]

Spot-price based DR increases the peak load of the main transformer by approximately 20 %. Furthermore, from the graph it can clearly be seen that volatility of load levels increases. In MV feeders the largest peak load increase was approximately 25 %. However, in terms of thermal limits of the conductors the grid will be able to cope with the load change. [62] Load increase encountered in distribution transformers varied more than with primary transformers. This is probably because of the uneven distribution of the electrically heated houses in the network. From total of 469 distribution transformers in the case area, 20 were already overloaded. [62] Application of Spot-price driven load control clearly increased the load levels of all the distribution transformers, but the percentual increases varied a lot. As a result multiple transformers become overloaded.

The load effects encountered with Spot-price based load control are not unique. On the contrary, similar effects are encountered with all other single market signal based DR systems too. [62] Results of simulations with control signals derived from retailer's balance management activity, reserve markets and balancing power market is presented in figure 21. It seems that regardless of the used market signal for the load control, the resulting effect is always increasing in terms of distribution system peak load levels. Even though the average increase in peak load might not be alarmingly high, in smaller scale the effects can be significant. For example, according to a study by Honkapuro et al, application of Spot-price driven demand response can as much as double the load level of individual distribution transformers. [65]

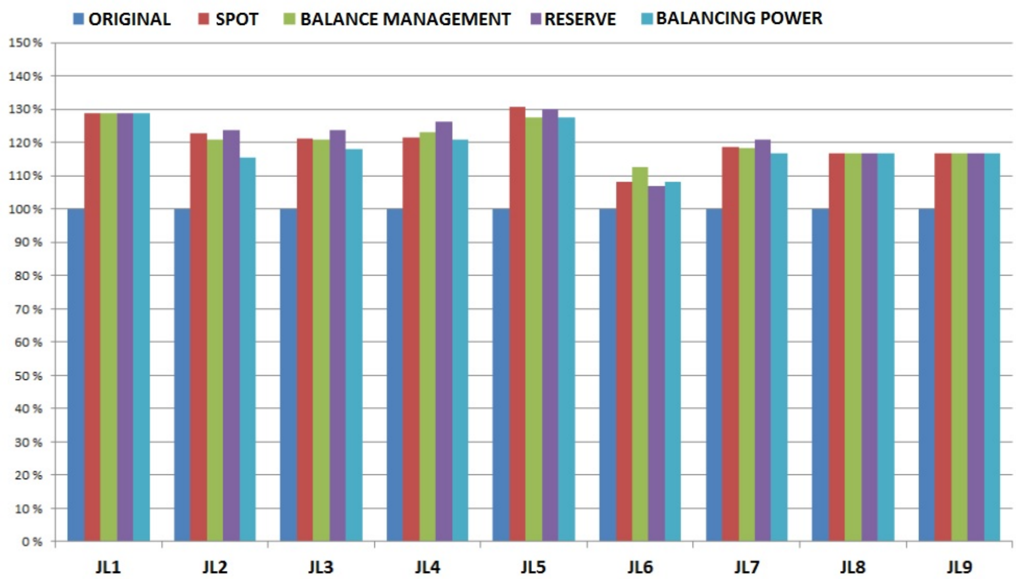

Figure 21: *Percentual change in MV feeding area load levels with different sources of control signal.* [62]

In order to avoid or even out the load peaks caused by retailer-controlled demand response, a power-based distribution tariff can be applied. With power-based tariff customer's distribution costs are adjusted according to their peak power demand. This would add an incentive for the customer to avoid large peak powers. Power-based tariff can be implemented with different levels of detail, which will affect the effectiveness of the instrument. For example a system that is based on monthly peak power will encourage the customer to monitor power consumption throughout the whole year while a system based on annual peak load will only affect powers during the coldest months.

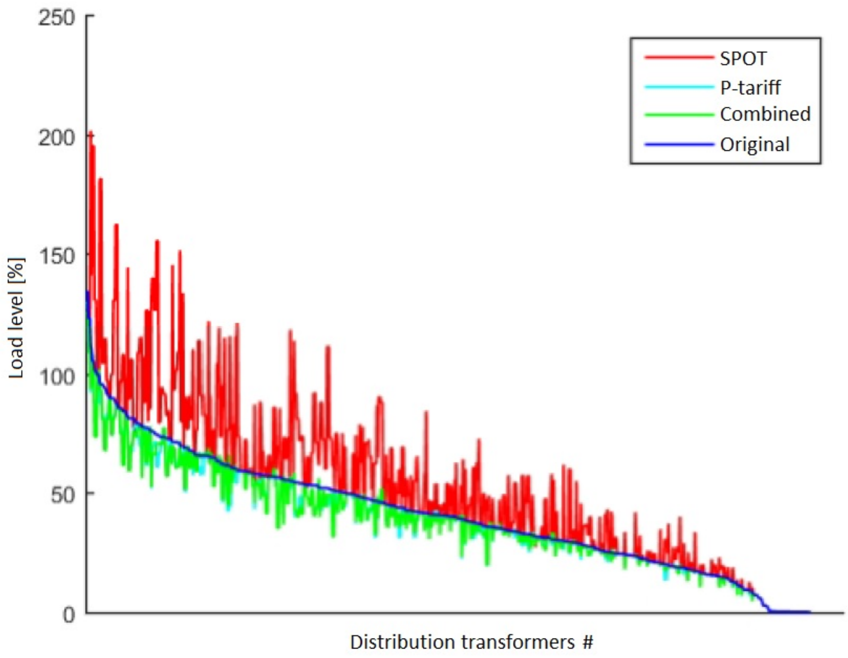

Figure 22: *Impact of power-based distribution tariff and Spot-price based demand response on peak loads of distribution transformers.* [65]

Figure 22 demonstrates resulting effect of introducing a power-based distribution tariff combined with Spot-price driven heating load control. It can be seen how application of only Spot-price based DR significantly increases the peak loads of the distribution transformers in question. However, by combining the DR scheme with a power-based distribution tariff the peak load increase can be prevented and furthermore, the peak load levels can even be decreased from the original situation. It is also notable that application of power-based tariff system without market price driven load control, does not produce as good results as the combination of the two. This means that from DSO point of view, the introduction of demand response might also provide positive effects depending on the structure and execution of the system.

Overall it seems that the impacts of demand response on distribution networks will be highly dependent on how the system is eventually formulated. Depending on the execution it can have a net increasing or net decreasing impact on peak loads in the system. Likely is, however, that regardless of system details the volatility of the loads will increase as a result of direct or indirect load control efforts. It seems that the the possible load increases will again have most significant effect to the distribution transformers. According to regulative authorities in Finland, DSOs' role in future DR system will be passive and they will continue to act as a provider of infrastructure and possible data required for the execution of the DR system. [66] However, the technical limitations of the network infrastructure will either way have to be taken into account in demand response execution.

Studies assessed here did not take into account the possible application of energy storage, microgeneration or electric vehicles. It is likely that these technologies will also play a large role in demand response systems. Penetration of electric vehicles and residential battery storages will add flexibility to customers' end which will enable more efficient DR system applications. Also, microgeneration and V2G will enable the system to not just adjust load levels, but also aggregate customer end electricity generation for the use of power system. Introduction of these technologies has, at least in theory, potential to reduce load volatility and peaks occurring with DR but again, the resulting impact is highly dependent on the execution of the system.

2.7 Data analytics and utilization

Data analytics and utilization have become a significant part of operation in every industry. Methods such as big data analytics and machine learning are being used to keep up with the increasing amount of information extracted from the operational environment. In distribution networks the amount of data being gathered is already substantial and is still expected to increase. The data is mostly used for network operational purposes as well as for asset management. Utilization of the existing data could however be improved and new applications can be developed. In this section the few different cases of utilizing existing as well as new data sources for new applications are assessed. However the possible applications of data utilization are not limited to the few example cases assessed here.

2.7.1 Load profile estimation and classification

Load profile estimations are extensively used by DSOs for network calculation and long-term planning. Traditionally load profiles have been formed based on for example customer type, fuse size, heating method and customer location. Classification can for example be based on a questioner and predefined load models, and all customers in the same category are assumed to have identical hourly load profiles. Usually around 20–50 customer classes are determined. Such profiling methods are rough and can produce substantial errors in load profile forecasts. Furthermore, once a connection point is profiled it is hardly ever assessed again, even though changes with for example heating method might be made. [67]

Big data analytics and machine learning have risen to be hot topics of the recent decade and can be utilized in load profiling and estimation too. Because of the huge amount of AMR metering data the load estimation and classification is one of the first operations that is likely to be improved. By utilizing gathered data, load classification can be based on computational methods and algorithmic clustering instead of predefined assumptions of the consumption habits. For example methods such as Artificial Neural Networks, Self-Organizing Mapping and K-mean algorithms have been applied to the use of load estimation and clustering. [68] Especially energy consumption based clustering and estimations can be done with a relatively high precision already. However, even though the load pattern estimations have improved and combined hourly loads of large customer clusters can be forecasted with relatively good precision, the load profile forecasting in the level of an individual customer is still unreliable. [67] [69]

With sophisticated data analytics and machine learning distinguishable load classifications or clusters can be identified and customers can be divided to segments according to their actual consumption habits. Machine learning can be applied to distinguish repetitive and classifiable qualities from the data set and therefore similarly behaving customers can be clustered under the same classification. Customer segmentation can be further classified according to the level of deviations and abnormalities in the data and therefore, reliability of the load and consumption estimations of each customer segment can be evaluated. However, high irregularities or deviations can not be forecasted by such methods. [67]

Due to high penetration of AMR meters, detailed data about load profiles has been available for approximately 5 years. This data enables the development of more precise customer profiling methods which will reduce the uncertainties of network calculation and enable more precise load forecasts for future planning. [67] With highly reliable load profile and consumption estimations electricity generation scheduling can be optimized and the day-ahead market will become more precise. For DSOs reliable estimations and classification methods can enable new operational models. For example it might be possible to allocate the billing principles according to the estimations and distribution costs could be unbundled from the actual metering data. Furthermore, reliable customer load classification can improve the quality of network planning.

2.7.2 Data utilization in network planning

In terms of network planning, the introduction of modern network information systems (NIS) has improved the quality of load data. In Caruna's case for example, measured hourly averages of the past year are used in every customer connection point of the existing distribution system. With actual measurement data of the consumption patterns it is possible to do accurate and realistic load flow calculations in the network. In case the consumption data is for some reason missing or new connection points are being planned, load profile estimations based on the type of the connection point are used.

A few dozen different customer classifications are used for LV network customers, and for customers connected to MV network, usually a case specific load profile is designed individually. The load models for different customer categories are also regularly updated based on the collected metering data of the customer class in question. Therefore, for example planning of a completely new network area can be done with reasonably high precision already. Additionally, it must be noted that in many cases the load is not the limiting factor while planning distribution networks. However, in most of the connection points measured data is available and therefore the application of load profile estimation curves does not introduce notable errors in the scale of for example an existing MV feeding area.

This system delivers sufficient accuracy of the load profiles for the use on network planning and the hourly consumption data is also stored from the past years. Therefore the system already provides a good data set which could be utilized in order to develop an accurate load classification and estimation system that could produce more detailed future load forecasts for long-term network planning and possibly even be applied as the basis for distribution billing.

2.7.3 Asset health and condition-based maintenance

Utilization and analysis of data can also enable optimization of grid maintenance process. Traditionally maintenance programs are based on time-based inspections and maintenance routines. Time intervals for specific grid components are mostly defined by information based on manufacturer's suggestions, historically determined practices or traditions as well as the significance of the component in terms of quality of supply. For some maintenance activities or components, time interval based inspections are a valid mode of operation. For example, tree trimming from the edges of OHL corridors can pretty safely be based on specific time intervals, as the growth speed of trees can be well estimated.

However, for some components time may not de a definitive factor in condition estimation and a time interval based maintenance program can lead to wasted costs due to large amounts of unnecessary inspections. It has been estimated that in US approximately one third of utility maintenance costs are wasted due to unnecessary inspections. [72] Therefore methods for utilizing the already available data from the distribution network operation and faults have been developed in order to optimize maintenance processes.

Reliability centred maintenance essentially means prioritizing maintenance programs according to the results derived from data analysis of the available datasets. This enables more precise and demand based allocation of maintenance resources, which optimally leads to less costs and better reliability of supply. Multiple different algorithmic methods have been developed for allocating the maintenance of the components. [72] [73] [74] Utilized data can be for example collected fault data from previous network faults, operational data from SCADA systems or AMR meters as well as system average interruption frequency and duration indexes. Usually all the optimization systems produce a more precise and detailed picture of the strategic components in which the maintenance process needs to focus on. However, even though the results of predictive maintenance optimization are better than what can be achieved with traditional methods, the system is still based on inspections and time interval based maintenance visits if component specific asset health monitoring information is not available. Furthermore, predictive maintenance based on algorithmic estimation models is only as precise as the quality of the data and assumptions being used.

Continuous asset health monitoring

Combination of big data analytics and asset health monitoring can further focus the scope of maintenance decisions. Eventually the goal is to shift towards a fully condition-based preventive maintenance process enabled by real-time asset health monitoring and big data based prognostics. Such process consists of three main functions: asset diagnostics, asset prognostics and decision making [75].

Asset diagnostics essentially means active health monitoring of the component in question. Monitored components can be anything from cables to circuit-breakers or transformers. The monitored parameters on the other hand can be anything from operational information already derivable from AMR meters or SCADA and DMS systems, to ambient parameters of performance such as temperature, vibration or sound. [76] With the set of desired parameters an asset health index (AHI) can be composed in order to evaluate and compare the health of different components. AHI composes of different measurement-based condition statuses that are put on a numbering scale. The results of these ratings are usually also combined to a single AHI value in order to gain a quick understanding about the condition of the asset in question. However, the comparison of the health indexes needs to take into account the whole detailed dataset or the richness of the available data will be lost. [3]

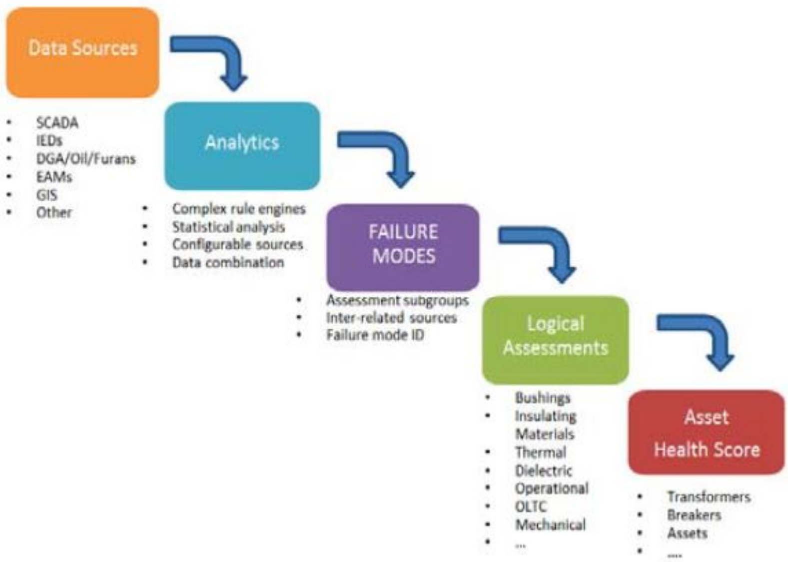

Figure 23: *Process model for refining collected data to an asset health index.* [3]

Asset prognostics is practically the analysis part of the process and it is where the collected data is processed to understandable form which will enable decision making. Practically the process utilizes methods of big data analytics and machine learning. AHIs for the grid components can be formed based on historical data gathered from all similar components. Biggest problem in defining AHI values is the definition of the original limiting values of specific conditions. For example in the case of transformers, acceptable limits for things such as dissolved gas levels in transformer oil may need to be determined, and furthermore interpreted what possible deviations from the reference limits indicate [3]. However, once the limits have been defined and set, anomalies in specific components can be identified by means of pattern recognition. [75] Because the system is based on historical data, efficiency of the fault detection increases over the time as the system learns from the continuous stream of data. Figure 23 presents a flow chart describing the AHI value determination process.

Based on asset diagnostics and prognostics, an estimation of the expected remaining life-time for the component can be made. Maintenance decision making can be conducted according to the achieved refined information. Depending on the age and condition of the component, it can either be replaced, serviced or neglected. Implementation of asset health monitoring will produce a detailed understanding about the life cycle of the components. Furthermore, with analytics of the gathered data, impact of different events and faults to the life expectancy of the components can be determined.

Optimally the whole process is integrated under one system, new or existing one, which will handle all the phases of the process and trigger alerts whenever there are components that need attention. With such system the computationally heavy process can run in the background while only the necessary pieces of information will be delivered to responsible parties.

Impact for the DSO

Even though some studies show that existing data from customer end metering devices and DSO's SCADA system can be leveraged to produce information about specific network components [77], it is likely that in the future additional monitoring investments will need to be made. For example, condition monitoring of distribution transformers based purely on already excising and AMR meter data analytics has been shown to be theoretically realizable, but with additional metering of for example heat, vibration and sound the results can be further improved. Therefore, at least in the early state of asset health information analytics, it would be beneficial to access as many parameters of a component as possible. That way the learning process could be improved and eventually it might be possible to identify incidents and degradation based on fewer measured parameters and historically determined analytical models.

For the DSO successful application of asset health monitoring and condition-based maintenance would bring clear benefits. Most obvious and direct benefit would be the cost optimization achieved in grid maintenance process. Furthermore, the operational efficiency of the maintenance activities would probably affect positively to security of supply, as component failures could be detected in advance. Overall, the gained information about the life cycle behaviour of the network components would allow a more detailed knowledge of the grid's condition and performance. For example, in the future investment programs attention could be focused on components or quality issues that have been discovered through the continuous condition monitoring. Additionally, more profound knowledge of the component behaviour under different conditions can be utilized in planning of the distribution network operation in order to maximize life spans of critical components.

2.8 Energy communities

In this thesis energy community is defined as a group of customers that participate in electricity retail market as a single entity and exchange electricity as they see fit within the community boundaries. Under current legislation such activity is not allowed, as for example conductors crossing property's boundaries are regarded as practise of distribution system operator business, and therefore subject to licence of regional monopoly. However, changes to the regulation restricting the formation of energy communities can be expected. [66]

There exists three different classifications of energy communities:

1. Community within a single property (e.g. apartment building)
2. Community crossing property boundaries (e.g. group of detached houses)
3. Distributed energy community (e.g. virtual energy community)

This section only focuses on the two first ones, leaving distributed energy communities out of the assessment.

Main motivation behind permitting and promotion of energy communities is to facilitate adoption of microgeneration. For example PV production in apartment buildings is usually not feasible, because under current regulation the electricity produced by housing cooperative's PV panels can only be used in communal spaces of the buildings. Feeding self generated electricity to the use of private apartments would require payment of taxes which usually makes investments infeasible. By forming an energy community within the property, in which every apartment participates, it is possible to freely distribute the self generated electricity to the habitants of the apartment building. Furthermore, this would also promote investments to bigger and therefore more economically feasible microgeneration facilities. [78] In addition to apartment buildings, similar principles can be applied to groups of detached houses or other housing methods.

From DSO's perspective this could mean that the community has only one connection point to DSOs distribution grid and the infrastructure behind the meter would be responsibility of the energy community. Schematics of such community in an apartment building is presented in figure 24. On the other hand, every customer needs be allowed to choose freely whether they are willing to participate to an energy community or not [66] and the possibility for every customer to choose their electricity retailer must also remain [2]. Therefore some problems in terms of who owns which parts of the network can be expected.

Disregarding the fact that customers will need to be able to leave energy community if they will, in principle it might be possible for the DSOs to renounce from installation of AMR meters to every apartment. In the eyes of the DSO energy commune would be regarded as a single, large customer. On the other hand behind the connection point to DSO's network, energy community would require a method for allocation of energy bills. Therefore, DSO's apartment specific AMR meters could be applied as a service for the community which enables fair distribution of costs within the community. This would enable new business opportunities for DSO as a provider of a energy community market platform and infrastructure. Furthermore, with long history of load modelling and forecasts, it could also be possible for the DSO to provide energy community market platform that is unbundled from the AMR metering infrastructure. This possibility will be further assessed in subsection 2.8.1.

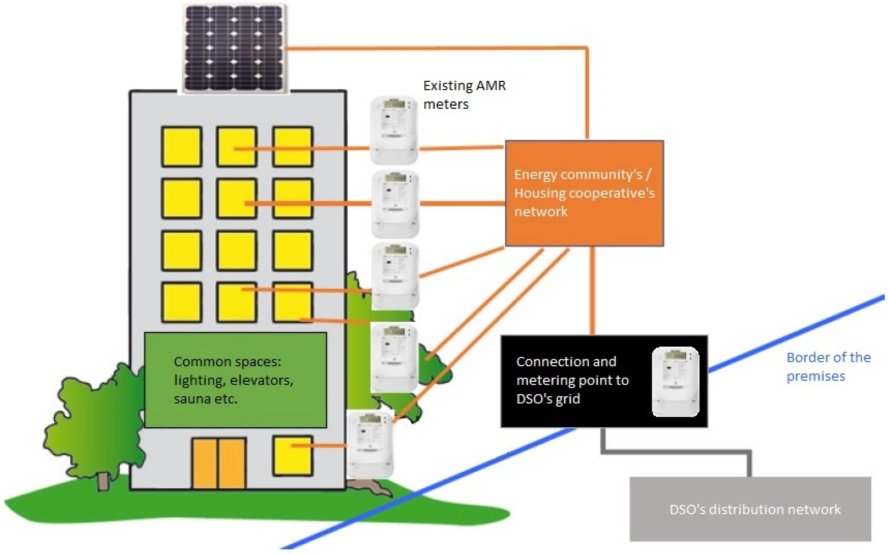

Figure 24: *Possible schematics of an energy community in an apartment building where all habitants belong to the community. Modified from.* [78][66]

Barriers for energy communities

There are some technical and regulative obstacles to overcome in order to adopt fully independent energy communities to the power system. The idea of fully replacing apartment specific metering devices with one attached to the main supply feeder of the apartment building can be questioned due to regulative principles. It is most likely that even while energy communities will be allowed they will be completely voluntary for individual residents. This means that for example a single apartment owner in an apartment building can choose not to participate in the community and is entitled to connect to the distribution grid on his own. Additionally every end customer must be allowed to choose their electricity retailer. This can complicate ownership arrangements of the network behind energy community's centralized meter as well as principles of possible microgeneration distribution inside the community.

There exists also other problems in the ownership arrangements of the community's network behind the meter. If the network behind the connection point to DSOs distribution grid is transferred to the ownership of the community itself, its members would become liable for operation and maintenance of the grid and would for example need to appoint a network manager to account for the safety and operation of the network. Such bureaucracy would likely limit the popularity of energy communes. Furthermore, if a habitant wants to resign from energy community the ownership of the meter and network connected to it should be shifted back to the possession of the DSO.

However it could be possible to form the community without transfer of ownership, which would provide a more concrete possibility for the DSO to act as a platform provider for the energy community market. It could also be possible to establish local energy communities completely virtually, utilizing the existing distributed AMR meters.

2.8.1 Estimation based cost allocation

Assuming energy communities will generalize in the future, advanced load and consumption estimations could be implemented in a platform for allocation of energy and distribution costs within an energy community.

Hourly consumption data has been gathered continuously, from customer connection points for multiple years, and therefore a comprehensive dataset is available for consumption and load profile forecasting. Accuracy of the estimations is highly dependent on the amount and quality of the data available, and with the current penetration of AMR meters the quality can be assumed to be reasonably good, and the quantity of data constantly increases [70]. By means of data analytics and machine learning the customer segmentation and energy consumption forecasts can be made based on historically measured consumption habits. Furthermore, from the recognized customer segments, the ones with the highest reliability of forecasts can be identified.

Within customer segments with high accuracy of consumption estimations, the potential for using forecasts as a basis of cost allocation could be feasible. Marginal level of uncertainty in the forecasts could be accepted by individual members of the community. Further, in the case of apartment buildings, customers often belong to segments with least disturbances in the estimated consumption profile, and therefore possible errors in the forecast could be cancelled out in the long run. This could lead to a situation where the AMR meters would not necessarily be needed in every apartment of the community. For example new generation of AMR meters would not necessarily need to be installed in apartments that belong to an energy commune. Furthermore, the savings achieved by not installing meters to every apartment could be included to the distribution prices of the specific community, which could eventually lead to lower overall distribution costs within the community.

The total consumed energy and energy balance of the commune can be measured with a single meter at the connection point to distribution grid and the distribution costs that need to be divided between the individual commune members in the area can therefore be defined precisely. Respective cost partitions of different commune members can be allocated according to the customer classifications formed by data-analytics-based load clustering which utilizes the historical meter data collected with current AMR metering stock.

Renouncement from customer specific AMR meters within energy communities would have positive effects from societal point of view and potentially bring economical gain for individual customers in the form of lowered distribution costs, as the amount of metering devices in the distribution grid could be decreased. For the DSO the economical impact within the limits of current regulation might actually be negative, as the allowed earnings are currently tied to the value of DSO's network assets [71]. The reduction of AMR meters would decrease the value of network assets which will further decrease the amount of allowed returns. On the other hand, in the long run maintenance and replacement costs of meters would decrease and by providing a market platform for energy communities' internal electricity exchange market, losses in network asset value could be compensated. Furthermore, with less dense placement of meters, the quality of metering data could be increased more cost efficiently, which would further enable more detailed monitoring of the distribution system. Resolution of metering data could more cost effectively be increased from hourly averages to shorter intervals or even real time monitoring.

Barriers for estimation based cost allocation

Problems with estimation based cost allocation may arise due to large changes in customer consumption, for example due to adoption of new large appliances. Even though forecasts can be made with reasonable accuracy to the near future, in longer time-span that might not be the case. For example in the case of detached houses, individual customers' investments in microgeneration would practically become unprofitable unless the consumption changes in individual connection points can be flexibly taken into account in the cost allocation and customer classification process. Similarly, acquisition of an electric vehicle or other changes in heating methods will have a significant impact on individual's electricity consumption. On the other hand, system that is based on aggregated consumption data might encourage formation of larger scale microgeneration systems for the use of the whole energy community.

Estimation methods based on historical data and machine learning will not be able to accommodate to large deviation in the dataset [67]. This means that some sort of process for updating the customer classifications would be needed in order for the load classification and customer segmentation process to be continuous. It is unlikely that for example a process based on customer oriented informing of DSOs about changes in consumption habits would work efficiently. However, for the use of energy community's internal cost allocation, much cheaper metering solutions could be applied than the regulated standard AMR meters. In such case the metering information could naturally also be applied as bases for the energy community market platform.

Model for operation principles of energy communities might not be complete and currently has unanswered questions. As it is not realizable under current legislation, it is likely that at least one more generation of AMR meters will be fully installed in customer connection points. In the scope of a 20–30 years, as the second generation of AMR meters reaches the end of their life span, situation might however be different and energy communities a functioning part of the power system.

2.9 Summary of the impacts

In this section the assessed changes will be summarized in terms of the possible impact caused to the distribution network as well as probability of individual changes. Different subjects will be compared with each other in order to achieve a better understanding of the relative magnitude of the impact. Furthermore, the combined effects of all the changes will be estimated and evaluated.

The subjects assessed in this chapter vary widely in nature. Some subjects are very concrete and tangible with direct implications to for example load levels or consumption. Other subjects on the other hand are very abstract in nature with usually indirect implications that can be hard to express, estimate and allocate correctly. Because of the mixed nature of the subjects, a general overview of the assessed changes is presented in figure 25. In the diagram the probability of individual changes as well as nature of the impact is estimated on a general level. The impact is evaluated from the point of view of technical performance of the distribution grid. In this figure the classification of the subjects is kept to almost minimal in order to gain a high level understanding of the changes and especially their relative positions.

Additionally, figure 26 assesses the impact of changes to the energy consumption and load levels encountered in the distribution grid. In this figure the classification of subjects is more detailed in order to produce a better view about the individual challenges within each main subject. It is also notable that some subjects do not inflict direct quantifiable impacts to power or energy consumption, but the effects will be of a different nature. Such subjects will be placed to origo in the diagram.

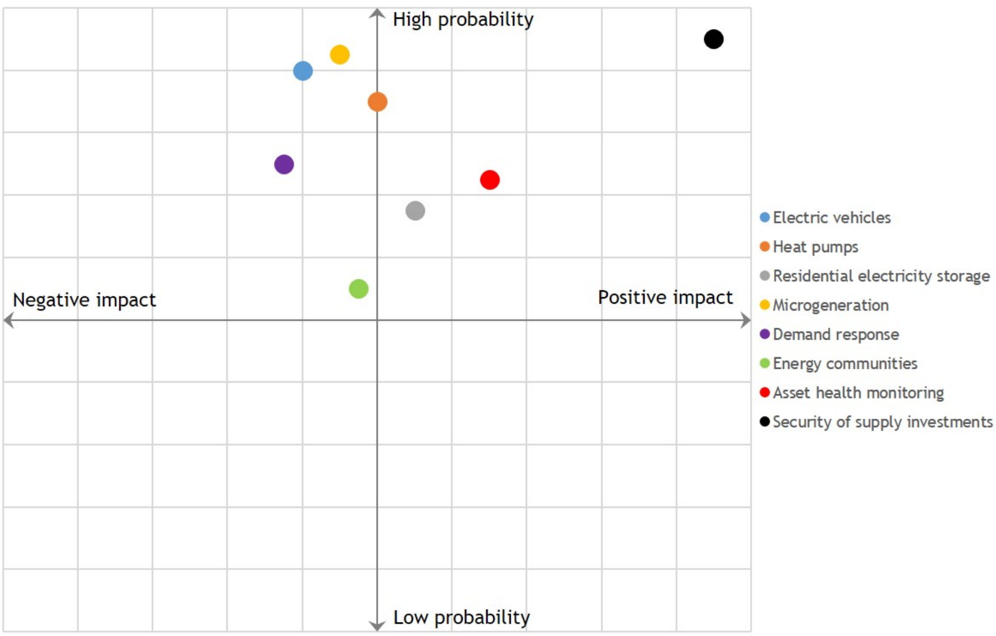

Figure 25: *Overall probability and high-level nature of the assessed changes. Scope of the assessment is set to year 2030.*

Security of supply investments

Highest realization probability has been set for the security of supply investments, which is obvious as a large part of the investments is already under construction or in planning. It is also evident that the impact of these investments will be positive to the grid in terms of better security of supply and new components with higher loading

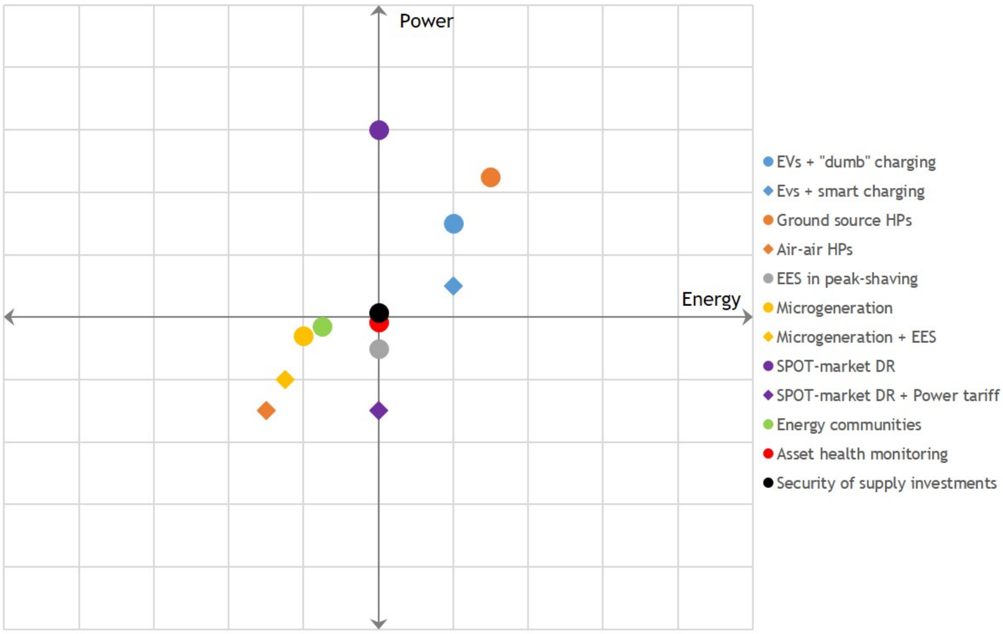

Figure 26: *Effect of changes to the power and energy consumption in the grid with a more detailed level of classification. Scope of the assessment is set to year 2030.*

levels. As the subject is not related to electricity consumption or customer behaviour there will be no direct impacts to power or energy balance, disregarding the fact that the capacity for grid loading will be significantly improved in the process.

Microgeneration

Second most probable change is microgeneration. It has been estimated to be in a braking point of its penetration and for example the level of PV systems connected to Caruna's grid has approximately doubled annually for few years. The penetration rate can be expected to be maintained in the near future, as incentives for growth by political decision making and general public has been set for it.

In terms of technical performance of the grid microgeneration will most likely introduce only minor challenges. With realistic forecasts of microgeneration penetration, problems in terms of component loadings and reverse power flows are not very likely and can not be considered as a general problem throughout the network. The effect will be marginal in terms of energy balance too, due to the fact that practically all microgeneration will take place during summer when the electricity demand is at its low. For this reason the annual peak power demand will also not be affected. Power quality issues on the other hand are little more likely and may cause problems to the grid mostly in terms of increasing voltages in LV feeders. It is also possible that reverse power flows may cause problems in terms of network protection and high-speed automatic reclosing. On the other hand, the need for hi-speed automatic reclosing is diminishing due to extensive underground cabling programs, as the emergence of faults which can be cleared by reclosing is decreasing. Overall the power quality and network protection issues will be case specific and there is no reason to assume that such incidents would be systematically encountered.

Electric vehicles

Probability of EV penetration to Finnish car stock can also be considered high, but it would seem that the rate of penetration in respect to the size of the car fleet will be relatively slow. The penetration percentage has been estimated to be between 4–8 % of the vehicle stock by 2030. With this in mind the possible impact to grid components' loading levels will be restrained even without any smart charging functionalities.

Biggest effect of load increases will be encountered at distribution transformers, where the encountered load increases will be in the scope of 0-2 %. Even though individual problems in the grid are still possible, the penetration of EVs does not introduce general concerns in terms of load increase. Similarly, problems in terms of power quality, such as voltage unbalance and flicker are possible but there is no evidence of systematic problems for this part and therefore no reason to assume any generalizable problems in the grid. Furthermore, the possibility of power quality an load peak issues can be mostly overcome with introduction of 3-phased smart charging.

Heat pumps

The increasing penetration of heat pumps in Finnish housing stock can also be seen as a very probable scenario. Figure 7 in section 2.3.1 shows the very aggressive increase of HP penetration in the past, especially in terms os AHPs, and there is no reason to assume that the adoption rate would significantly decrease.

In figure 25 the overall impact of HPs has been evaluated to be neutral. This is because the the AHP and GHP technologies will affect the load levels in the grid very differently. In short, AHPs will be installed mostly to direct electric heated houses and therefore decrease the average load levels caused by space heating, while GHPs will mostly be replacing oil heating, which in fact has potential to significantly increase the loadings in residential areas. Whether the net result is increasing, decreasing or neutral, is hard to predict and is entirely dependent on the heating methods that are being replaced. However, in terms of current adoption trend the net result will in fact decrease the overall demand of electricity. Anyhow, at least a large part of loading caused by GHPs will be compensated by load reductions achieved with AHPs. Furthermore, power quality issues due to HPs are individually possible but again there is no reason to assume a wide spread of problems in the grid. Additionally, slow-start functionalities and 3-phased connections can reduce the probability of power quality issues.

Demand response

By 2030 demand response can be considered to be functional part of electricity system. However, the determination of the system principles and boundary conditions is currently under discussion, and therefore decisive implications to distribution networks are hard to predict. Currently there remains a lot of open questions about execution of the system. For example the signal source for the control procedure, market platform and the actual operating platform for the control functionalities is still open. Furthermore, the role of the DSOs in the mix is not fully determined yet. It is likely that the final DR system will be realized with help of aggregators that aggregate customer side flexibility assets in order to participate in different reserve markets or a completely new, separate flexibility market. Aggregators can be either already existing electricity retailers or completely new market participants. The role of DSOs in the system is still open, but it is likely that they will not be allowed to act as active market participants in DR. However it is possible that DSOs can participate as providers of the infrastructure and data platform for DR.

In the assessment it was assumed that SPOT-market price (and reserve market prices) will be used as control signal of DR system. In figure 25 the overall technical impact to the grid is considered to be slightly negative, because it has been shown that SPOT price signalled load controlling can significantly increase the peak load of the distribution system if limitations of grid components, mainly distribution transformers, are not taken into account. However, by introducing incentives for load level based control, such as power-based distribution tariff or assigning customer specific power bands, it is possible to restrain load increases or even achieve peak load reductions. This can also be seen in figure 26 where the two cases are presented separately. In terms of energy DR should have no impact as the basic principle of the system is to shift the demand to more desirable time. Overall, as the definition and details of the DR system are still largely under development, at the moment there is no reason to assume extensive problems arising for the distribution grid.

Asset health monitoring

With increasing amount of underground cables and expectation of large load variations in the future, asset health monitoring can be expected to emerge as a part of grid operation, security of supply and maintenance optimization processes. Asset health monitoring will not have direct impact to either power or energy demand, but it has significant potential in increasing the efficiency of current operations. Continuous health monitoring of critical grid components can enable detection of upcoming component malfunctions and network faults, therefore providing possibility to act in advance, improving security of supply and decreasing repair costs. Additionally, it enables allocation of maintenance programs according to the actual need instead of time-based inspections. The final penetration and feasible applications for asset health monitoring are highly dependent on the development of data-analytics and monitoring hardware. Additionally the implementation costs of such systems will eventually determine how widely it can be adopted or in other words, on which network components it can feasibly be implemented to.

Electrical energy storage

The amount of residential electricity storages will likely increase but the magnitude of the penetration will remain to be seen. There are currently no credible estimations or forecasts about the penetration of customer side electricity storage available. The eventual development in EES adoption will be largely affected by the price development of battery technologies. However, due to increasing amount of municipal solar electricity systems, net amount of customer end storage capacity can be expected to increase.

Residential EES systems can be seen as a positive change in terms of technical performance of the distribution network. Main functionalities for battery storages will be customer-oriented peak-shaving and integration of microgeneration systems. Essentially both operations will have a slightly reducing effect to peak load demand of the residence, therefore reducing the possibility of congestions in the grid. In peak-shaving the battery storage will be charged during cheap hours of low electricity demand and discharged during peak demand. Similarly, when integrated to a PV system the self-use of PV production can be maximized and peak load level can be decreased. Additionally, the amount of excess production being fed to the grid can be minimized. This improvement in microgeneration performance can also be seen in figure 26 in terms of larger power and energy demand reductions of "Microgeneration + EES" compared to simple microgeneration.

Energy communities

How common energy communities become in power system will remain to be seen and advancement rate is highly dependent on the development of the regulative aspects. The resulting functionalities of energy communities can be argued and it is possible that the final result will be only a system where community members are free to exchange self generated electricity but participation to electricity retail market will still be individual. Nevertheless, the formation of at least some form of energy communities can be seen as a more probable than improbable result.

There exists business opportunities for distribution companies in realizing the energy community market platform, whether it is used for allocation of all electricity or only the exchange of microgeneration. In the scope of approximately a decade it is likely that the effects of energy communities will not be significant in terms of peak power or energy consumption. Effects are mostly caused by self use of microgeneration and therefore the energy consumption is slightly lower and the peak powers are affected mostly during summer months. With communal ownership of generation, investments to larger generation facilities are possible. Furthermore, due to the fact that in a community the self use rate of the generation can be expected to be larger due to large dispersion of independent consumption, the amount of surplus energy being fed to the grid in an ideal case can be expected to be smaller. Overall the technical problems caused by energy communities will most likely remain marginal.

Conclusions

Overall none of the changes stand out as a source of evident problems in the distribution network. It seems that the state of Finnish grid infrastructure is so good that at least individually, the predicted changes in the power system will have only little effect even with over ambitious assumptions of penetration levels of different technologies. Taking into account the unified effects of all the changes, it is possible that for example load increases can cumulate to produce higher power peaks in the system, but still in terms of the limitations of the grid, the encountered change will likely not cause any general or systematic problems. Similarly there seems to be no reason to assume any systematic issues in terms of power quality or network protection.

Local and case specific problems may occasionally arise, for example in a situation where a whole neighbourhood or an apartment building switches heating method from oil or district heating to ground source heat pumps. However, such incidents can be handled individually and require no strategical actions in the network construction and operation. It can also be concluded that in the cases where load increases become a problem, distribution transformers are the first components to become congested, while plenty of room for loading still remains in feeders.

Main reason for the durability of the grid under the assessed changes is to do with the dimensioning of the network that is traditionally done according to the needs of direct electric heating. Furthermore, it seems that the ongoing large network investments and current network planning and construction principles are effective in further reducing the possibility of problems in terms of load and power quality issues. Overall capacity of the grid improves, while also separation resolution of faults and the amount of backup connections increases.

As the upcoming changes do not induce any acute or wide-spread problems to the current network infrastructure, the IoT applications required can be dimensioned correspondingly. Focus of IoT applications can be shifted to being able to detect and recognize the possible individual problems that may arise in the grid and therefore being able to react to such situations in advance. Furthermore, developing and improving current processes and operations can be assessed.

3 Introduction to IoT

Internet of Things is a buzzword that can nowadays be heard in variety of contexts, but in fact the concept has already been around for few decades. [79] Fundamental idea behind the concept is the penetration of everyday objects, living things and eventually the whole physical world to the realm of the internet. From business point of view, such connectivity will provide completely new applications which enable new business models, cost savings and enhanced processes. The definitions of the concept can slightly vary depending on the source of the information, and also terms such as Industrial Internet, Internet of Everything or anything in between these can be encountered. In fact, many big corporations seem to be creating personal acronyms for their products and services, but essentially the idea behind all of them is the same. In this thesis mostly the term IoT will be used.

3.1 Development and trends

The number of internet connected IoT applications is already significant. There were total of 16 billion devices connected to the internet in 2016 of which approximately 6 billion were identified as IoT devices. [1] [80] The amount has been expected to increase rapidly in the future and according to different forecasts the number of connected IoT nodes in 2020 will be between 14–20 billion. This represents approximately 30 % annual growth in number of connections. By 2020, the percentage of customer-end IoT devices has been estimated to be 63 % while the rest will be intended purely on business purposes. Figure 27 presents the estimated growth rate of internet connected IoT devices and the growth in total internet traffic.

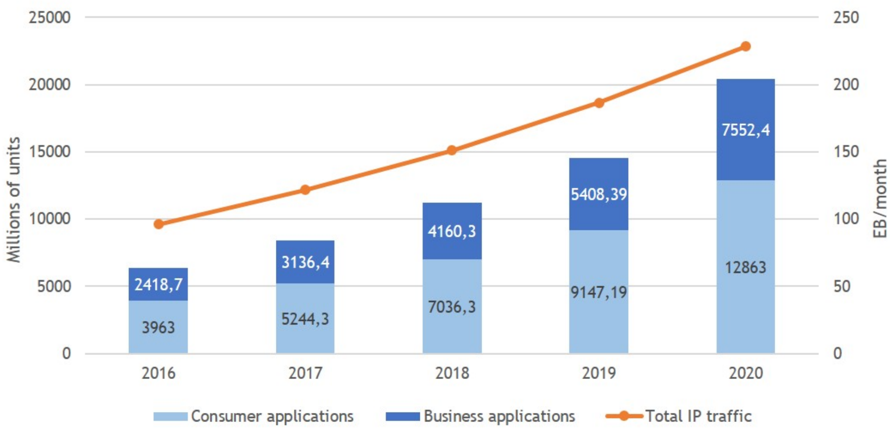

Figure 27: *Estimated growth rate of connected IoT devices* [81] *and total internet traffic in exabytes.* [80]

Similarly, the growth can be detected in global spending on IoT technologies. In 2016 the global IoT spending was 1,38 billion dollars and in respect to growth in the number of IoT devices, also global spending is expected to increase. It has been estimated that by 2020 spending has more than doubled to 2,93 billion dollars.

Figure 28 presents this growth which amounts to annual increase of approximately 20 % in global spending. Also, where as consumer applications cover larger quantity of end devices, at the moment the business sector dominates the spending. However, by year 2020 it is estimated that the spending of consumer and business sectors will be approximately equal. [81] From this it can be deducted that on the average business applications may be fewer in number but are more intelligent or sophisticated compared to consumer side applications.

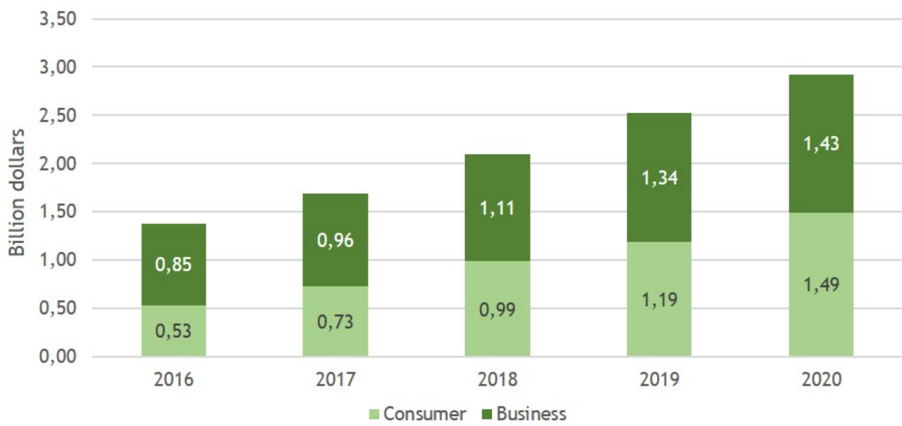

Figure 28: *Forecast of global spending on IoT technologies.* [81]

3.2 Architecture of IoT system

IoT is a system which connects both inanimate and animate physical objects to the internet. The objects can be anything from running shoes to industrial pumps or farm animals. In order to connect and extract data from everyday things or objects, sensors and communication methods are needed. Furthermore, in order to gain value from the gathered and aggregated information, also data management and analysis methods such as cloud computing and and big data analytics are needed. In the end the actual application will utilize refined data from the cloud. [82] Figure 29 describes a standard architecture of an IoT system. In fact, the architecture can be roughly divided into four layers:

1. Sensor network
2. Gateway and communication
3. Data management and cloud computing
4. Applications

Increasing variety of sensors and wireless sensor networks (WSN) are one of the main enabling technologies of the IoT. From the beginning of the 21st century the cost of sensor technology, similarly to other electronics, has decreased significantly which has enabled wide-scale utilization of sensors and data extraction. [83] Sensors and actuators are the devices that enable the collection of data from the "things" in Internet of Things. Collected data can be anything from heat, moisture and chemical composition to location, movement as well as video and audio. However, the source of the information does not necessarily have to be designated sensors completing specific tasks, but for example a smart phone can act as an actuator or an end node of the system, by utilizing its integrated sensors. The underlying factor with the wireless sensor networks is that the amount of end nodes in the system will eventually become huge therefore increasing the amount of data being collected to similarly overwhelming levels. [84] In principle the network of sensors is not necessarily required to be wireless, although many of the applications, such as GPS tracking usually only become possible or feasible with wireless sensor networks. Further, the vision of connecting practically everything to internet can only be achieved with wireless networks.

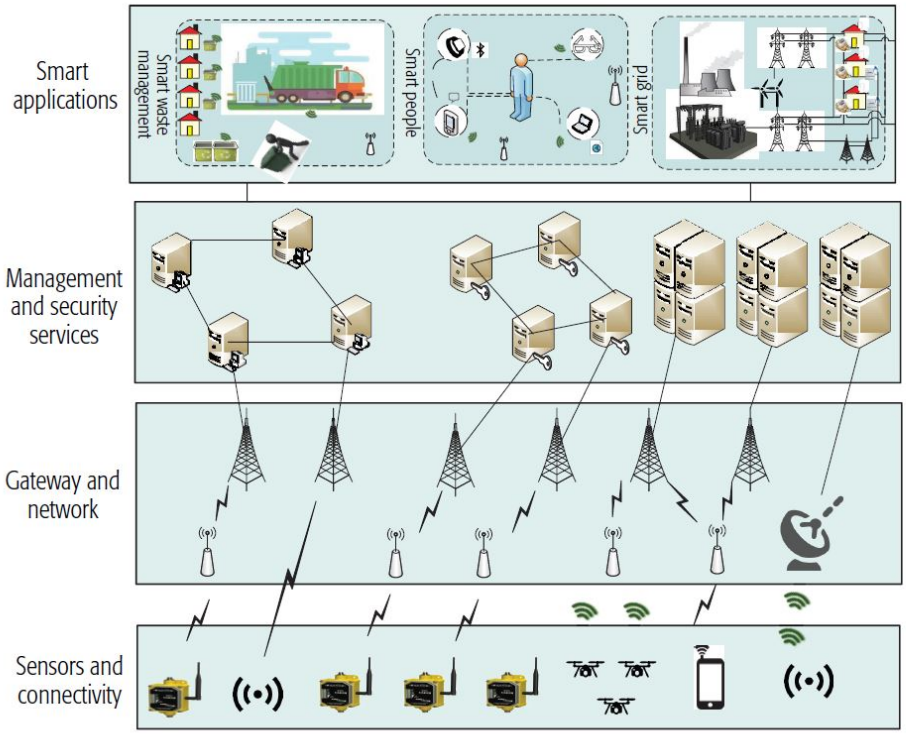

Figure 29: *Typical architecture for Internet of Things system.* [82]

Second layer of the system covers the communication methods of the collected data to the use of data management and eventually user applications. The use of WSN itself requires a communication method for the individual sensors to transmit data. In case of short range local communication, technologies such as RFID, Bluetooth, ZigBee, or Wi-Fi can be used to form a connection to the gateway that provides a backhaul connection to the cloud or server. For longer distance communication, technologies such as GPRS, LoRaWAN, 2G, 3G and LTE can be used. [84] There exists a number of different wireless communication technologies that all have advantages and disadvantages. Selection of the preferred communication technology can be dependent on many things such as, the required latency of the applications, energy usage of the sensors, cost of the technology etc. In principle, all technologies produce the same results as in the end the data gets sent through a gateway device to the desired destination in the same format. This means that utilization of different technologies in the same system is possible.

The amount of data produced by IoT will be enormous compared to the traditional internet usage. End nodes and sensors of the system will be acting as extractors and messengers of data and due to limitations of computing power and energy usage at the end nodes, the actual computing will be done in a centralized system. Direction of the computing architecture in IoT applications is heading towards cloud computing based system, where the computing process is carried out in a virtual cloud, formed by possibly spatially distributed servers, and computers. [85] This means that the traditional architecture of delivering data to a single server or computer that can be accessed by the specific application will be renounced. With a cloud based data storage and computing the huge amount of low-quality data extracted from the sensor network can be processed efficiently and in real time. These big data processing methods will be able to refine the continuous stream of low-quality data to a more usable form, providing possibility for fast and continuous decision making [83].

Application layer of IoT system utilizes the pool of data in the cloud. Compared to traditional vertical systems which collect, process and present desired data in specific silos, the cloud based systems enables horizontal utilization of data. All applications can be allowed to use the same, real time data from the cloud which enables development of versatile and more comprehensive applications. Furthermore, with a comprehensive cloud of data the machine-to-machine communication in an IoT system will increase. Traditionally internet communication has only happened between person-and-person or person-and-machine, but the horizontal availability of data enables the machine-to-machine communication to complete automated processes without involving users. [86] This makes it possible to enhance the usability of the applications by only delivering the information necessary for the user's decision making process.

4 Utilization of IoT technologies

Scope of the assessment in this thesis is limited mostly to the utilization cases of sensor technologies. Due to limitations of length in this thesis, for example technical specifications and different communication technology alternatives are mostly left out of the assessment. The main objective of this is to present utilization cases and possibilities of different IoT applications on a general level and asses their feasibility from different viewpoints. Furthermore, the current readiness or ability to adopt an IoT based measurement or monitoring system is evaluated, and the requirements for such a system assessed.

Applications assessed in this thesis can be divided into two groups: operational applications (section 6) and asset management applications (section 5). Operational applications focus on improving grid operation aspects and introduce new possibilities or increased knowledge about the operational and possibly even dynamic state of the network. Asset management applications are focused on enhancing and improving the knowledge about the durability, lifetime and life expectancy of network components. Furthermore, asset management applications can improve existing processes and focus on decreasing operational expenditures (OPEX) of the DSO. In section 4.1 architectural system requirements for an IoT system or platform are assessed from Caruna's perspective and the assessment is mostly focused on realization of an asset health and condition monitoring system.

4.1 Architecture design for IoT based monitoring system

General principle for IoT based asset health and network state monitoring system's architecture is demonstrated in figure 30. Overlaying idea is to form a cloud based system that is able to combine data from multiple sources and produce reliable information from the distributed data streams. Majority of the necessary data for formation of for example AHI is extracted by additional sensors which are installed on the device, depending on type of the component. Applications that visualize and utilize the refined information in the cloud can be either completely new applications or API integrations to existing information systems.

Essential idea behind the cloud based platform is to be able to combine information from the IoT sensors as well as countless already existing ICT systems in order to promote openness in the system and to avoid further formation of systems that work in parallel in specific silos. With application of a dynamic and easily integrable cloud based pool of data, the utilization of data from all sources becomes possible and full potential of analytics can be enabled to the use of for example big data analytics and machine learning algorithms. The richer and more versatile the available database is, the easier it is to produce valuable results.

4.1.1 Sensors and communication

Sensors and sensor networks can be seen as the neural network of the continuous asset health and condition monitoring system. It is not likely that reliable and precise

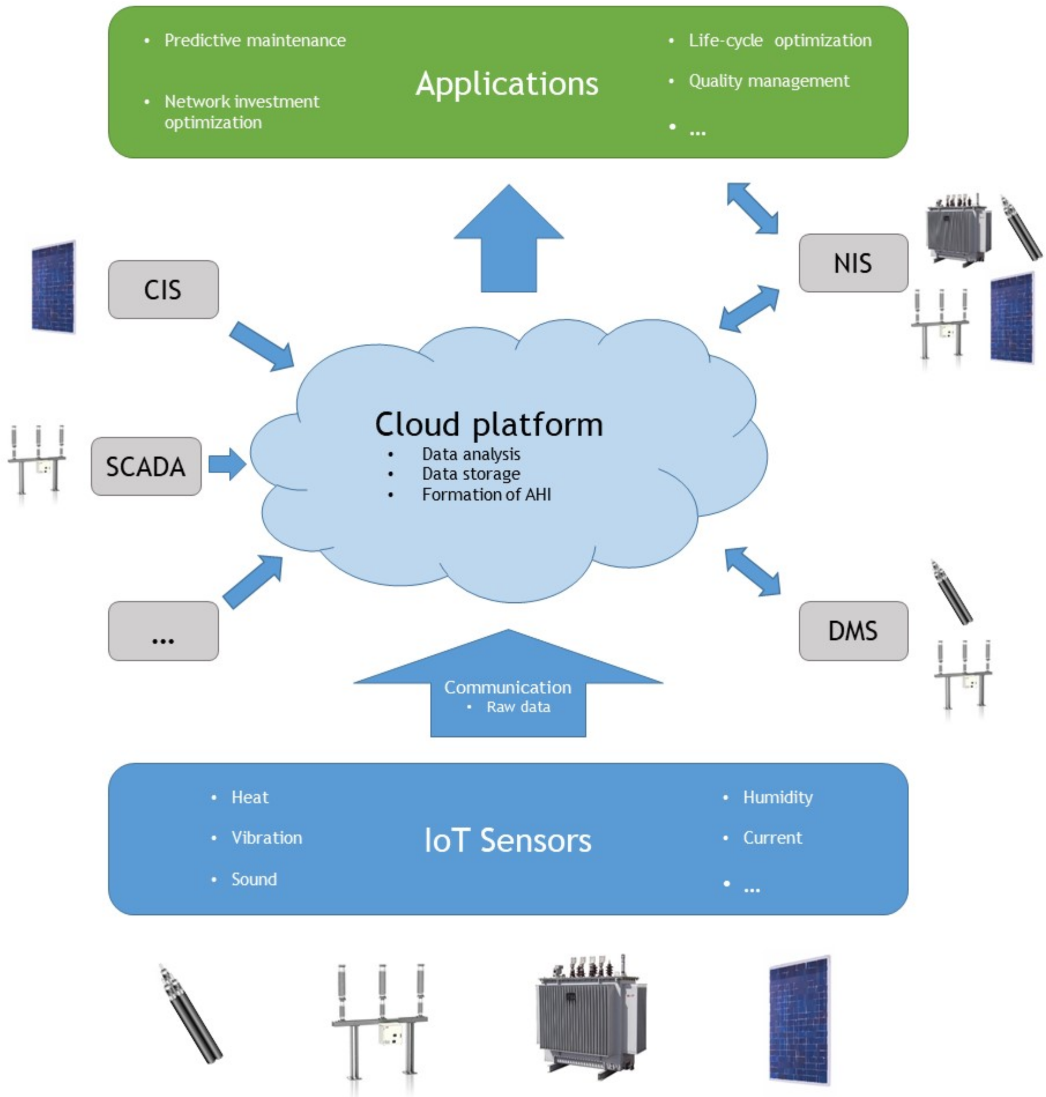

Figure 30: *Overview of a possible architecture for asset health monitoring process in electricity distribution company. Component pictures in the the figure represent, were all the information of the specific component is distributed.*

enough information could be extracted purely by means of analysing already existing data from different information systems, and therefore installation of additional measurements is important. In most of the application cases accessing the condition and health information of a component directly is not possible or it can not be feasibly executed, and therefore indirect measurement of relevant parameters are used. Combination and analysis of these environmental and ambient measurements produces the information needed for determining the desired health information.

In most applications the indirect ambient measurements consist of parameters such as heat, humidity, vibration, noise and operating current. Depending on the case also parameters such as movement, light, ultrasound etc. can be measured. Unifying factor for these parameters is that firstly they are easy to implement without large modifications to the component or its protective structures, and secondly the prices of such common sensor hardware has decreased rapidly during the last years. For example, in order to measure vibration or operation temperature of a component, in most cases it is sufficient to simply attach the small sensor to the body of the component. Attachment can be done for example with help of a magnet or glue, without any need for drilling or opening the component structure in question. Most typical sensor hardware, such as heat and humidity sensors can currently cost as little as 0,50 € depending on the size of the batch bought. [87]

Use of indirect measurements in asset health monitoring is actually more productive than determination of only mechanical consistency of the component. It has been shown that many of the fault situations of different components show some kind of symptoms or signs of the upcoming failure in advance. Therefore, through application of indirect measurements these symptoms can be detected and the fault situations reacted to in advance. Early reaction to component failure situation often also leads to smaller maintenance expenditures compared to the situation of a full failure. In distribution networks the prevention of component failure will also result to savings in avoided supply interruptions. Figure 31 shows an example of the symptoms that are encountered during failure advancement phases of a power generator. These symptoms are however typical specifically for rotating machines, and therefore can not necessarily be generalized to distribution network components. [88] Nevertheless, the same principle should be exploitable for network assets too.

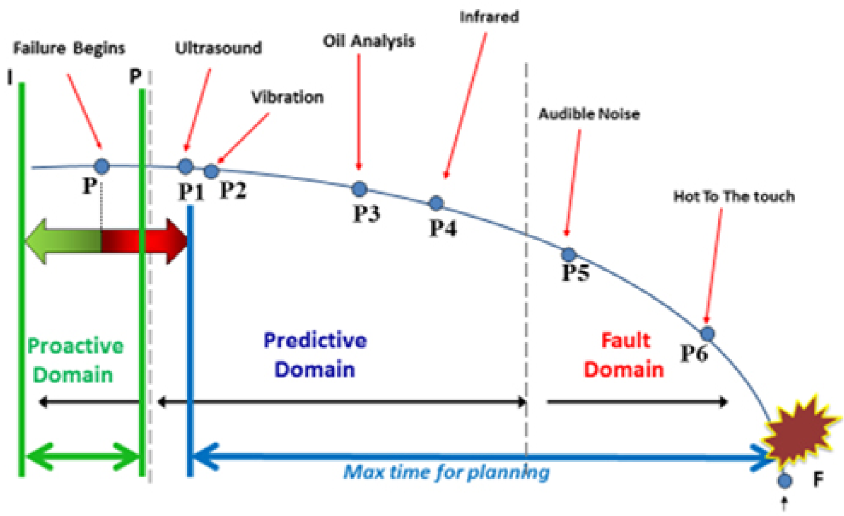

Figure 31: *Symptoms encountered before the full fault situation in rotating machines. Earlier the failure can be detected, the cheaper the maintenance costs will also be.* [88]

For the part of communication the applications of continuous condition monitoring can also be slightly more challenging compared to cases where the measurements take place in a clearly confined space. In a confined space such as a factory or a power plant it is possible to use sensor networks based on short range and high capacity, such as BLE or WiFi, but in case of for example distribution substation surveillance such technologies would hardly be feasible as the gateway connection point would be added for each measurement site. Depending on the amount of data that needs to be transmitted, also low-power wide-area networks can be used, in case the data transmission quantities remain within the capacity limits. On the other hand, condition monitoring applications taking place at primary substations could utilize the shot range sensor network communication, and the amount of measurements per gateway device could still be relatively high, as there are a number of critical components situated at a single substation.

4.1.2 Data analysis and system integration

The overall operation and feasibility of, especially asset health and condition monitoring system, is largely defined by the operation of the analysis part of the architecture. In order to be able to refine the raw data into useful information, the data analysis must be properly defined and have enough computational power as well as access to sufficient amount of data. [3] Therefore, a centralized cloud based pool of data has a clear advance as it offers a unified source for all the necessary data to be stored and processed. The cloud platform should also be developed to maximize the integrability of data and provide easy APIs for data connectivity. In addition to providing easy access to existing data systems, this would also enable flexible addition of third party measurement solutions to the cloud and the analysis. Open and easily integrable data platform would therefore also enable the platform owner not to centralize all operations under only one or few system suppliers, and for example piloting of smaller data acquisition systems could be easily implemented.

There are two general methods for analysing the data and determining the health and condition of a component: online and offline method. In an offline method usually at least part of the analysis is carried out by a human being, an expert who possesses the knowledge about the proper operation of the component in question and is able to distinguish possible anomalies or problems in the measurement data. This sort of approach can be used is situations where very few, high value components are being monitored. In such case the amount of data needs to be limited and within the grasp of one or more experts. Furthermore, such monitoring can often take place retrospectively, when anomalies are already noticed.

On the other hand, online method that can be used for truly continuous and large scale monitoring of wide variety of small and large components, demands automatization of the analysis process. In a system that continuously measures and monitors distribution grid components the amount of received data will easily grow to huge amounts, which can not be controlled and assessed by human beings and therefore automated analysis and possibility for system's self-learning can be seen as highly beneficial. Flexible access to data from different sources also truly enables the application of big data analytics as well as current and future AI and machine learning systems. Application of sophisticated data processing methods can also be seen as a future requirement in order to access the full potential of the condition monitoring and asset health analysis.

Even with automatized data analytics, the system needs to be adjusted with a set of initial values which act as the basis of the analytics. In other words, the system needs to be able to understand normal behaviour of the components in order to recognize anomalies in the operation. Generally the values can be determined by studying literature and standardisation or by consultation of experts. It is also possible that the component manufacturers have developed operational models of their product which can be used. [89] Initial values or a model for normal operation can also be determined through a wide enough measurement data set of similar components. If sensors are applied to large enough sample of similar components, the anomalies in the data can be recognized by comparison of different measurements.

4.1.3 Application layer

Applications in application layer act as data visualization tools in of the whole systems. In an ideal case the applications therefore act only as user interfaces to the information that has been processed in the cloud platform and no computation or or heavy analysis processes are being carried out in the application layer. This kind of architecture makes the applications very light and therefore enables usage of the system from many different type of devices. Furthermore, as all applications utilize the data from the same pool, the amount of overlapping computing and data storing can be reduced.

An important aspect for the usability of the system is that the user will not be overwhelmed with useless information, which means that the data processing and parametrisation needs to be done in a way that the user will only see and access relevant information. Idea of the system is to deliver more information and knowledge, opposed to just producing a vast amount of additional data. A common approach in existing asset health and condition management systems is to utilize graphical interpretation methods of data. Through graphs and colour-coded expressions it is easy for the user to achieve a quick understanding about the state of the component or a group of components. As asset condition monitoring can encounter sudden state changes of critical components, it is also beneficial that the system is able to deliver quick notifications about the occurring anomalies in critical component operation. This will enable user to take action before a full failure occurs.

It is also possible to integrate results from the cloud analysis in existing information systems through APIs. In figure 30 this is demonstrated with two-way arrows from NIS and DMS to the cloud platform. In Caruna, NIS is currently the main information system in the use of asset management and therefore a two-way integration between the asset information in the cloud platform and the NIS would be beneficial. The whole fleet of company's network assets, from HV to LV components is documented in the software system and therefore it would be natural for the condition data of the components to be present in the component properties.

In this respect some of the applications derived from cloud based analytics could be run in the existing system, which is demonstrated in figure 30 with a double sided arrow to the application layer. NIS system could present mostly some non-acute component information, such as life-cycle and life expectancy analytics that do not require fast responses from the network operation perspective.

DMS on the other hand could benefit from the integration of component health information in a more real-time sense. For example the encountered operational anomalies and failure flags could help with network operation planning, which is executed using the DMS. In the figure other information systems, including SCADA, are presented with a one-way arrow which expresses that they act only as providers of data to the cloud. It is however possible that other information systems would also benefit from condition information. For example notifications of emerging faults could be beneficial in the SCADA, but on the other hand the system is already quite full of notifications and alerts and network operators are struggling to keep up with the information. In this respect addition of asset health notifications to the information mix could be challenging.

4.2 Possibility for power quality measurements with AMR meters

Up to certain resolution, low voltage network power quality can be tracked with already installed AMR meters in customer connection points. In addition to power consumption metering, AMR metering infrastructure is able to measure power quality events such as: neutral conductor faults, over and under voltages, over currents, disconnected phases or wrong phase orders, supply outages and reverse energy being fed to the grid without informing the DSO. In terms of PV generation derived voltage deviations, especially unauthorised microgeneration and over and under voltages are of interest.

Due to characteristics of the metering technology and implementation of communication, the achieved power quality measurements can not necessarily be done in real-time. In practice the power quality measurements can be accessed retrospectively from previous days measurements. This is due to the fact that the metering information is updated to Caruna's information system once per day during midnight. General process structure of the AMR meter information collection is described in figure 32.

Individual AMR meters gather consumption and power quality event data to internal memory in packets consisting of four hours of measurements. After the four hour packet of a specific meter is completed, meter informs the data concentrator, and the concentrator retrieves the package from the meter. Data concentrators are usually located in secondary substation of the LV network in question. Communication between AMR meter and concentrator uses Power Line Communication (PLC), which means that the signal is delivered through the existing LV distribution network. Therefore, the data concentrator has to be connected to the same LV network as the AMR meter, as the signal can not be transmitted over distribution transformers.

The metering data is synchronized from the data concentrator to DSO's meter management system once every 24 hours, during a few hour period after midnight. Communication between data concentrator and meter management system is done

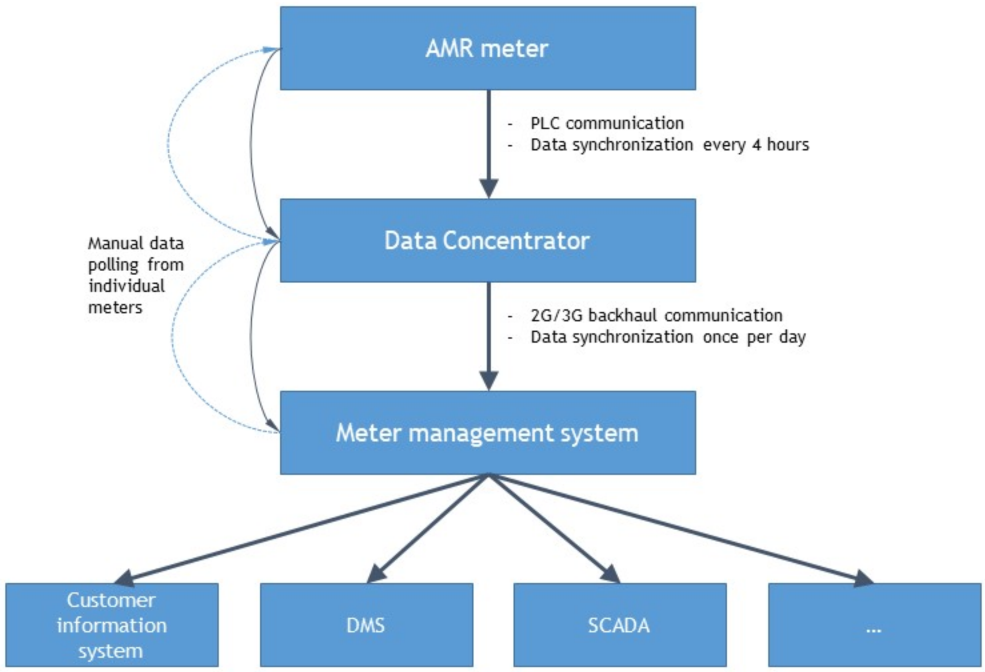

Figure 32: *General schematics of data collection process from AMR metering infrastructure.*

using traditional 2G or 3G mobile network. From the meter management system the power quality and consumption data is distributed to desired user application systems. 24 hour synchronization cycle means that in practice, the event data available for DSO can only be accessed retrospectively from previous days. However, some events can be identified as high-priority events. In case of such events, the AMR meter will send an immediate indication to the concentrator, which immediately retrieves and delivers the data to the meter management system. In Caruna's case neutral conductor and phase conductor faults are classified as high-priority events.

PLC connection can be considered to be relatively unreliable communication method, and from time to time the connection link between the concentrator and meter can not be formed. Therefore, the AMR meters are also able to preserve a number of packages in their internal memory. Duration which the packages can be stored in the meter's memory varies from multiple weeks to multiple months, depending on the resolution of the consumption measurements and the number of measurement channels being used. Therefore it is also possible that delay or latency of high-priority event notifications to the metering system becomes long. In this respect the applicability of AMR-meter-derived information in grid's operational decision making, where the response times usually need to be fast, can be compromised.

In addition to high-priority events, measurement information can be manually polled from individual AMR meters. A request can be sent from the meter management system or other systems integrated to it. Successful connection results to AMR meter transmitting its current measurement information to the system. However, due to the uncertainties in PLC communication operation, it is possible that connection to the meter can not be formed and the request stops at the data concentrator. In this case, the current real-time information from the meter can not be acquired and the most recent 4-hour measurement package available at the concentrator is retrieved.

AMR meters are able to provide a comprehensive overall view of the power quality events in LV networks retrospectively, with a delay of 24 hours. Due to very high penetration of metering infrastructure, a detailed picture of past events in the grid can be easily formed. Additionally, events in specifically chosen areas can be monitored with smaller sampling times by utilizing the manual polling functionality of the meter management system. For example the DMS software used by Caruna is integrated to the meter management system, and enables polling of power quality event information of desired locations. If a connection can be formed, the latency from meter to the DMS system can vary from few seconds to minutes.

There are also limitations to the quality and resolution of measured events. Current system is able to for example determine the event times and durations with resolution of one second, but the retrievable information about the event itself is more limited. Meters are assigned with trigger values for different events. Power quality issue is registered as an event only when the specified trigger conditions are realized. For example in order for voltage sag or voltage swell event to register, voltage level must remain outside the ± 10 % threshold limit of nominal voltage U_n for a period of 5 minutes. Furthermore, only the peak deviation from nominal voltage value of a registered event is reported. Therefore, shorter voltage quality issues and deviations can not be recognized with the measurements done by current stock of installed AMR meters.

The trigger values of AMR meter reporting can not be significantly altered to produce higher quality and resolution data from the events. Stricter event trigger levels would result into huge amounts of additional event data to be transmitted through the existing PLC communication path and preserved in device memory. Due to the huge number of meter installations as well as limitations of PLC communication and meter's internal memory, a more detailed event measurement could cause congestion in communication network as well as in AMR meter memory and meter management system. Furthermore, the current level of event information is sufficient for achieving an overall view of the power quality problems and introduction of stricter event trigger levels would require processing and filtering of the received data in the meter management system.

To conclude, current generation of AMR meters can be best utilized to identify and locate clear power quality problems retrospectively and therefore, they can for example be used to pinpoint LV networks with clear and recurrent power quality problems. However, due to the lack of real-time data, the AMR meter stock is hard to utilize in any real-time and operational decision making or voltage control applications. Furthermore, due to the limitations in power quality event trigger levels, the quality of for example voltage information in the LV grid is limited, and detailed information about voltage behaviour can not be retrieved.

5 Asset health and condition monitoring system

General principle and schematics behind application of asset health monitoring was already introduced in section 2.7.3. Essentially it is based on assigning an AHI for a network component in question. AHI score can be assigned using multiple parameters which when combined and analysed determine the health and operational status of the component. Parameters used in formation of the AHI can be extracted by additional measurement and surveillance equipment that are installed just for the purpose, or they can be parameters which are already extractable from the existing measurement or ICT systems, such as AMR meters or DMS. Underlying idea is that the monitoring is continuous so that possible complications can be swiftly detected. However, as it was already stated in section 2.7.3, it is unlikely that already existing data in DSO's information systems would be sufficient to compose a reliable and accurate image of the component's health and therefore additional measurements will be needed.

In this respect, IoT based sensor applications offer an easy and relatively cost effective way to extract additional data from grid components. Continuous condition monitoring is already relatively widely used for example in processing industries to measure and monitor operation of for example manufacturing processes or other industries with large and expensive machinery, such as electrical drives. In such cases the benefit has been evident and therefore similar practices are gaining foothold in other industries too. As the electricity distribution industry is highly infrastructure based and asset dependent it is a naturally promising field for continuous asset health monitoring applications.

5.1 Motivation for condition monitoring

Main motivation in continuous asset health and condition monitoring is to reduce costs originating from component failures and suboptimal maintenance and servicing programs. In process and manufacturing industries, where the expensive and system critical high value components are concentrated under same roof and the determination of the most expensive and system critical components, such as electric drives, is easy, continuous condition monitoring has been able to produce cost savings that can be measured in millions of euros.

Similarly in distribution network applications the main motivation would be to prevent network faults and to enhance the maintenance process. However, in distribution networks, similarly evident high-value and high-priority components which are operationally critical and possess a great risk to the whole system are not as evident as in process industry applications. Network assets are distributed over a very large area and there are no single components in which the performance of the whole operation culminates to, in the way that for example electric drives in process industries. However, in terms of security of supply, substation components are most critical, and therefore it would be a natural place for application of condition monitoring to begin with.

Through continuous asset health and condition monitoring of network components it is possible to form accurate and fact based information about the operational condition of the components and create a model of the life cycle that specific components have. Continuous surveillance and knowledge of the standard operation behaviour of the components enables recognition of anomalies in the operation and makes it possible to apply preventive maintenance procedures. This sort of information will increase the security of supply in the network, as the symptoms of malfunction can be recognised in advance and thus the fault situation can be avoided. Furthermore, maintenance of the components is usually more cost efficient when no major breakage has yet occurred.

As discussed earlier, continuous condition monitoring therefore enables transformation of maintenance process from time-based inspection to requirement based preventive maintenance. In stead of applying time-based servicing inspections to components with time intervals from months to years, it is possible to allocate the need for maintenance and inspections according to the information produced by the condition monitoring system. Even though physical time-based inspections could not be entirely avoided the number and frequency of such visits could be decreased, and prioritisation improved. This will potentially save a significant amount of resources that can be allocated to more productive use.

Continuous surveillance of the assets is also much more reactive compared to the time-based maintenance model. With time-based inspections the possible problems and deficits can only be found during the scheduled inspection visits or complete component failures. As the inspection visits are usually done with intervals of several months to several years, depending on the criticality of the component, it is possible that arising signs of upcoming component failures can go long times unnoticed and develop into full component failures causing network faults or supply disruptions. With sufficient continuous monitoring early signs of the upcoming failure can be detected at any time, regardless of the inspection intervals, and therefore reacted to before fault is encountered.

Additionally, knowledge of component performance and lifetime behaviour can improve the specifications made for future component acquisitions as the possible problems in existing component stock can be recognised. Similarly it can be used for quality control by ensuring the proper operation of new network components. With sufficient information it could also be possible to plan network operation procedures in a way that will maximize the life span of critical components. Furthermore, the achieved information about active condition of the grid can be utilized in grid investment planning and prioritisation process.

5.2 Circuit breaker condition monitoring

One of the potential components for application of condition monitoring in distribution networks are circuit breakers. Circuit breakers (CB) are automatically operating switches, which protect the network from over currents that might be harmful for other network components. Typically over currents are caused by fault situations such as short circuits and earth faults in the grid.

Circuit breakers can be seen as critical components in ensuring safety of the network and fast restoration of power to the grid in fault situations, which has direct effect in customer interruption costs experienced by the DSO. Due to the big structural changes in the grid and improvements in security of supply, the overall operation frequency of circuit breakers can be expected to decrease. High underground cabling rates lead to fewer network faults which decreases operation frequencies of circuit breakers. However, due to the requirements of the new electricity market act the proper operation of protection becomes even more critical during the fewer fault situations, as the costs from interruptions increase. Therefore, continuous condition management and availability of component health information would be highly beneficial in ensuring the operational readiness of the circuit breakers.

Systems for monitoring the health of circuit breakers have in fact been available for a long time already, but they have tended to be expensive and operating as individual systems, deriving information only from independent measurements. [90] An IoT sensor based system would have potential to significantly lower the costs of such a system and increase the integrability. There is also a notable amount of research done about utilization of single measurement parameters to the use of condition monitoring, but studies about the use of multiple parameters in determination of component condition are fewer in number. In studies focusing only on utilization of a single parameter, in most cases the reliability of the condition assessment is concluded to be somewhat unreliable and a large number of samples as well as complicated analytics are needed. By combining measurement of different operational parameters, the reliability of the monitoring could likely be improved.

Most studied parameter for CB condition monitoring is coil current or motor operating current monitoring with a current sensor. For example with trip or close coil current measurements, it is possible to determine peak current values for the coil as well as the operation times for excitation, auxiliary contact operation and the whole energizing time of the coil. By comparing these parameters with a normal operation state of a CB it is possible to recognize failures in for example voltage supply, latch operation, coil resistance and mechanical operation. [91] Through current measurement of motor signal current it is possible to determine precisely the realized operation time of the CB, which can be compared to the set tripping time settings, and possible deviations in the operation time can be detected. By using clip-on Hall meters for current measurements, the sensors can be attached non intrusively also into old and already operational CBs. [93]

Another valid measurement parameter for CB condition monitoring is vibration. Vibration patterns of different CBs can be compared with each other similarly to the case with current measurements, in order to identify abnormalities. Vibration can be measured with an accelerometer which can be attached directly to the body of the circuit breaker in a non intruding way. With vibration measurements the achieved signal can be analysed in order to produce the timing and velocity of the closing operation. However, as the measurement is purely mechanical there there can be a large amount of noise interference in the measurements which can complicate the precision of the analysis. [94] The analysis of the vibration signal concentrates on the timing of the noticed events and assessment of frequency domain, and the actual vibration amplitude, which is easy to visually determine, is of less significance. [95]

In addition to the two parameters described above, there are a number of other measurements that could be carried out. For example radiometric measurement to determine duration of the arc, dynamic contact resistance measurements, contact force and erosion measurements, as well as dissolved gas analysis on oil CBs and gas pressure measurements in SF6 insulated CBs, can be used. However, many of these measurements require modifications to the integrity of the component and the measurement equipment can be costly. [94] Heat and humidity measurements would be a cost effective addition to the measurement palette, but their benefit can be questioned especially in the case of outdoor substations. One additional interesting parameter for condition monitoring is the possibility of using sound wave analysis in the monitoring system. It has been stated that utilization of microphones in CB monitoring can further enhance the reliability of the health analysis [96].

5.2.1 Suggestion for measurement parameters

In Caruna's network there are over 3600 circuit breakers and therefore, the easy execution and cost effectiveness of the condition monitoring system and data extraction should be paid attention to. In this respect it is evident that at least current and vibration measurements should be utilized, as both parameters can be measured non intrusively from old and new components, and the informative value of the measurements is clearly stated in literature. Also, vibration sensors can be installed to the surface of the component, which enables analysis of mechanical operation of the circuit breaker. Table 2 lists the suggested sensors and their applications.

Table 2: *Suggestion for IoT sensor based measurements for circuit breakers.*

Sensor type	**Application description**
Current	Motor signal current measurement Trip and close coils current measurement
Vibration	Mechanical operation characteristics
Temperature	Control panel cabinet temperature
Humidity	Control panel cabinet humidity

Current sensors should be placed to measure at least motors operating current, which will enable the determination of precise operation times of the component. If accessible, sensors can also be placed to trip and close coils, which will enable a closer analysis of the performance with only current measurements. Vibration sensor on the other hand should be placed on the surface of the hull of the CB. Combination of vibration measurement and motor signal current can be efficiently used to determine the realized operation times, which can be compared to the component specific set-values. Furthermore, through vibration analysis of the operation, abnormal mechanical behaviour of the CB can be detected.

Even though temperature and humidity measurements might not prove to be very efficient in determination of the CB health, they could still be implemented because the cost of the sensor hardware is so small. Temperature and humidity could for example be measured from inside a control panel cabinet of the circuit breaker, which could help to ensure safe operation conditions for the equipment inside.

For formation of AHI of specific CBs also background data from existing information systems should be utilized. General information such as age, coordinates, manufacturer and model, as well as technical parameters and rated capacity of the component can be retrieved from DSO's NIS. Trip settings for short-circuit and earth fault currents are available in the DMS and from SCADA the realized historical operation events of a specific CB can be retrieved. With combination of this information and the additional online measurements of the component a detailed AHI analysis should be possible. Similar monitoring applications could be applied to the surveillance of remote controlled disconnectors too.

5.3 Secondary substation and distribution transformer condition monitoring

In chapter 2 it was concluded that distribution transformers are the most likely component to encounter congestion in the developing distribution network. Even though ongoing security of supply investments result to replacement of almost all pole mounted transformers with ground mounted distribution transformer cabins and freshly dimensioned transformers, it was concluded that large changes to load behaviour in individual feeding areas can cause over loading in transformers. Therefore, asset health and condition monitoring application to the surveillance of distribution transformers can be feasible.

Generally the existing monitoring systems are largely applied to the use of high voltage power transformers located at substations, while applications to distribution transformers are clearly fewer in number. Application of monitoring systems to power transformers is a natural approach, as the criticality of the component is much larger in terms of effect area of a possible failure, compared to distribution transformers. In Caruna's network there are 263 power transformers and over 31 000 distribution transformers. This ratio can be expected to be approximately the same in other networks too, and therefore it can be safely assumed that some of the more expensive measurement equipment that can be feasibly applied in power transformer condition monitoring, can not be economically utilized in distribution transformer monitoring.

Most of the asset health and condition monitoring systems intended for power transformers heavily rely on measurements and analysis of insulation oil. [97] For example, dissolved gas analysis (DGA), oil humidity and oil temperature can be measured. DGA can produce a precise composition of different gases that have dissolved in the insulating oil. [98] At least gases such as hydrogen, oxygen, carbon monoxide, carbon dioxide, methane, ethane ethylene, acetylene and moisture are widely measured. [99] From the concentrations, indications of at least general degradation, decomposition of paper insulation and appearance of partial discharge or arcing can be concluded. [98] Heat levels of oil on the other hand have been directly linked to the life expectancy of the component. [100] Unfortunately, direct oil quality measurements can not be carried out non intrusively and modifications to the component structure are needed in order to access the oil. Therefore, application of oil measurements to distribution transformer monitoring can be challenging from practical and economical perspective.

Partial discharge measurements are also widely used in power transformer condition monitoring. Detection of PD can be done relatively non intrusively and it is an indication of fault situations or failures inside the transformer. Separation of internal and external PD is important in order to avoid false alarms. [98] However, PD measurements are comparatively expensive and complicated, which can act as a barrier in distribution transformer applications. Furthermore, the measurement data is complicated to analyse and usually human expertise are required, which means that execution of automated diagnosis can be challenging. [101].

In stead of measuring the insulation oil temperature directly, which requires modifications to the components integrity, the hot-spot temperature of the insulation can be determined by indirect temperature measurements of the transformer hull. [102] However, the results achieved from direct temperature measurements from the insulation oil are much more reliable and for the use of external temperature measurements an approximation model of components thermal behaviour needs to be used. Hot-spot temperature is the limiting factor of transformers load capability and it is caused by overloading or local overheating. Too high temperatures also reduce transformer's life expectancy. [99]

It has been shown that monitoring of noise produced by a transformer can be utilized to asses the health and condition of a transformer. Transformers produce a humming noise during their operation and by combining the abnormalities and changes in the recorded sound with other measurement parameters, more reliable picture of the operation conditions of the component can be formed. Sound is analysed in frequency spectrum, where abnormalities and changes in humming frequency can be easily detected. Changes in frequency are normal and vary in respect to the loading of the transformer. By comparing the noise analysis with transformer load information, anomalies indicating for example mechanical failures can be recognized. [103] Similar results could be extracted by using accelerometers for vibration monitoring.

As mentioned, in determination of the operational status and condition of a transformer, the loading data is necessary. In order to compile a realistic model of component condition the indirect measurement parameters need to be correlated to real-time loading data. [103] Load data can be extracted either by individual energy measurements installed at the secondary substation or it can be retrieved from existing load data and grid automation systems, depending on the state and reliability of the DSO's information systems.

5.3.1 Suggestion for measurement parameters

Number of distribution transformers is even larger than the number of CBs in the grid and therefore easy installation and cost-effectiveness of the measurements is even more noteworthy. As far as possible, the measurements and sensor choices should focus on easy and non-intrusive installation process. Therefore, for example direct insulation oil temperature, oil level and DGA measurements should be avoided. Parameters of asset health and condition monitoring application for distribution transformers could consist of external temperature, load and noise measurements. In addition, historical and operational data from existing information can be used. For the surveillance of the secondary substation premises, similarly temperature and humidity sensors can be utilized within the cabin as well as a door sensor, to determine whether the cabin door is closed. Suggested IoT sensor based measurements and their applications are listed in table 3.

Table 3: *Suggestion for IoT sensor based measurements for secondary substations and distribution transformers.*

Sensor type	**Application description**
Temperature	Indirect transformer oil temperature measurement Substation atmospheric temperature measurement
Humidity	Substation atmospheric humidity measurement
Energy	Transformer load measurement
Sound	Transformer humming noise analysis
Door sensor	Substation locking verification and access control

Temperature measurement could be executed non-intrusively with external measurements. As mentioned, the measurements from the component hull are not as reliable as direct oil temperature measurements, and therefore a pilot case which combines internal and external temperature measurements could be useful, in order to determine the correlation between inner and outer temperatures. In the pilot case, temperature sensors could be placed directly to the insulation oil, on the surface of the transformer tank and to the transformer cabin, in order to measure the ambient temperature of the space. With such combination, it would be possible to form a model that describes the correlation between the actual oil temperature and the temperature at the surface of the transformer. Humidity measurements inside the cabin would produce additional data about the conditions in the technical space. Room temperature and humidity can also provide valuable information about the operation of the ventilation system of the space.

Acoustic noise sensor could be utilized to detect abnormalities in the sound frequency spectrum of the transformer. Sensor should be placed to the utmost vicinity of the component itself, in order to minimize interference in the recording. Viable information can be gathered with fairly normal and low cost microphones [103].

Viable utilization of sound analysis and thermal information will require precise enough load data of the transformer. Therefore an energy measurement in the secondary substation can be required. Energy measurement can be implemented with standard voltage and current measurements. In principle, it could be possible to extract loading information of the distribution transformers from the AMR meter management system, which would require no additional sensor installations. However, as described in section 4.2 the real-time application and reliability of the communication of the data acquisition system can be questionable and therefore utilization of existing information can be challenging. Furthermore, the load information retrieved from AMR meters consists of hourly averages, which is not necessarily detailed enough.

If a measurement system is implemented to a secondary substation, it means that a communication gateway will need to be installed for the use of the sensors. In order to increase the feasibility of the whole monitoring and measurement system, it is beneficial to install as many sensors as technically and reasonably possible to gather additional information from the site. Therefore, if distribution transformers are placed under monitoring, it is suggested to also add additional atmospheric temperature and humidity measurements to the premises. In this respect also for example door sensors for ensuring proper lock-up of the secondary substation door and tracking movement and access at the site could be implemented.

Due to vast amount of secondary substations, determination of sites and distribution transformers to be placed under monitoring should be picked according to load data derived from existing information systems. It is not possible to apply condition monitoring to all distribution transformers, which is why applicable components need to be recognized. Transformers with high risk for overload as well as those with high probability of normal operation should be picked in order to create versatile base for comparison.

Similarly to the case with circuit breaker monitoring, background information about the specific properties of the distribution transformer in question can be retrieved from existing information systems. In case of distribution transformers the primary source of background data is NIS, from which at least age, location, manufacturer and model, as well as technical parameters and rated capacity of the component can be retrieved. Final health score of the component can be formed largely based on correlating temperature, noise and load information together, while the background information enables reliable comparison of different transformers.

5.4 Underground cable condition monitoring

As explained in section 2.1, the amount of underground cables in Caruna's network is rapidly increasing due to the new security of supply requirements. As a result of increasing amount of cable network, the absolute quantity of cable faults will naturally also increase which can already be seen from figure 2. Even though more reliable than OHLs, there will be faults in cable networks too and usually repair work takes more time compared to OHL faults, as the localization and access of underground faults is more challenging. By being able to monitor cable conditions and predict possible unexpected failures, significant cost savings and security of supply improvements could be achieved, which would be in the interest of the DSO and the customers alike.

Traditionally, majority of cable condition assessments are based on PD measurements. However, PD measurement equipment are comparatively expensive and therefore their application is mostly based on requirement based offline measurements, conducted during inspections or when a fault or failure has already been detected. Such PD measurements can be conducted for example with an oscilloscope or spectrometer and they require the cable to be taken out of service. [104]

There are however also PD measurement based condition monitoring equipment meant for continuous online cable monitoring. One of the techniques is based on two inductive PD sensors, which are placed at the opposite ends of the cable line under surveillance. The monitoring range can be multiple kilometres and there can also be secondary substations between the two measurement points. PD events are very fast and therefore, the sensors need to be sensitive enough to recognize amplitudes of millivolts with frequency response of tens of MHz [104]. Pulses caused by occurrence of PD in the cable section travel to both directions and are measured with both PD sensors. By comparing the measured amplitude and timestamp from both sensors, location of the PD source can be calculated with accuracy of up to 1 % of the measurement distance. Time synchronisation of the sensors is highly important and the time difference of the measurements needs to be smaller than 100 ns [105] This requirement leads to a relatively high unit costs for a continuous monitoring set-up and prices can be as high as 30 000 €. [104] Reflecting this to the extensive amount of MV underground cable network there already is, it is evident that such high costs will not be feasible for systematic use in the MV network. It is however possible that the expensive online PD measurement could be feasible in the HV cable network, where the relative outage criticality and CIC are higher.

There are also takes on lowering the equipment costs for PD measurements. In [104] a low-cost PD monitoring systems for MV cables has been developed, which is able to recognize PD pulses with similar reliability as 8 bit oscilloscope. However, the localization of the fault source can be challenging with such a system. Nevertheless, a low-cost monitoring solution could be utilized in continuous monitoring application to flag problematic cable sections and afterwards a more precise offline measurement could be carried out to determine the precise location of the PD source. This approach would lower the cost for the measurement hardware as the requirements for time synchronisation would be less critical. In [106] such system is studied with a number of Rogowski coil sensors distributed along the cable network, dividing the grid to line sections. Sensors are able to recognize the direction of the PD pulse which enables localization of the PD source to the line section level of preciseness. Exact location of the source can be determined through traditional offline PD measurements.

Due to the high cost of traditional online PD measurement systems, alternative methods for cable condition monitoring have been developed. However, many of the alternative solutions to cable condition monitoring have not been fully productised and may only be implemented in laboratory conditions or early field pilots. For example a method of determining cable condition through high frequency insulation resistance measurement has been applied. This method is mostly suitable for monitoring of LV cables and it requires a signal transmitter at the secondary substation and a receiver at the other end of the cable. A frequency fingerprint of the specific cable is formed after the installation and continuous measurements are able to determine if unusually rapid ageing process is detected. However, there is only a very limited amount of cases where such LV cable monitoring system would be economically feasible. [107]

An other interesting approach to cable condition monitoring is thermal monitoring of MV cable joints. Cable joints are the single most fragile and failure potent part of the underground infrastructure of a cable network. It has been shown that by combining real-time loading data, temperature of the joint as well as ground temperature and weather data, a prognostic model for predicting cable joint health and failures can be created. Developed system has been able to predict hot-spot and possible failure occurrences with approximately half hour time horizon. [108] In addition, methods such as tangent delta, damped AC and impulse voltage measurement that have been applied for cable condition monitoring with moderate success. [109]

5.4.1 Suggestion for measurement parameters

Partial discharge based monitoring system can be considered to be the most reliable and technologically feasible choice for MV underground cable condition monitoring. Due to the vast amount of cable network that constantly increases, there might however be challenges with the economical feasibility of such system. At least the most expensive continuous online measurement tools, which are able to precisely locate the fault, will likely be beyond economical feasibility in most parts of the MV network.

A more cost efficient and simple approach for PD measurements might be the sort of distributed current sensor system described in [106]. By renouncing from the ability to precisely locate the fault sources, a more simple solution for online monitoring can be achieved. Induction current sensors with high sensitivity and frequency response can be placed with sufficient intervals along the cable network. Sensors should be placed for example at cable terminals, so that a pair of current sensors is used to monitor a single line section. By using Rogowski coil sensors the installation can be done non-intrusively due to the clip-on structure of the sensor [109]. Sensors can be placed at MV cable terminals at secondary substation and as the sensors are able to detect arrival direction of the pulse, the fault location can be recognized with a precision of a single line section. In case the measured PD pulses are found to be critical and further action needs to be taken, the exact location of the fault source can be determined with more precise offline field measurements. Such online PD measurements can be carried out over network components too, and therefore it is possible to detect faults which are originating from for example distribution transformers too. Table 4 presents the main points of the suggested measurement scheme.

Table 4: *Suggestion for IoT sensor based measurements for underground cables.*

Sensor type	**Application description**
Current	Placement to cable terminals at secondary substations • High sensitivity and frequency response PD detection • Non-continuous measurements, few times per day • Exact location of fault with separate offline measurement

Due to the required high sampling rate of the measurements, the possibility for actual real-time measurements can be questioned. If for example whole MV network of a substation is equipped with PD measurements the amount of data will be very large and transmitting and processing this data can be challenging. However, as the changes in PD can be assumed to change in long time periods and they mostly indicate about changes in cable's life expectancy, measurements could be carried out with regular intervals of for example 12 or 24 hours, which will reduce the burden of communication and analysis. [106]

In order to be able to locate the specific line sections producing PD pulses, information about the geographical location and topology of the network are essential. This information could be extracted from the DSO's NIS with sufficient reliability. If the sensors are placed to each secondary substation's MV feeder, the geographic location of the sensors can be assigned from the substations information. Similarly NIS holds the topological model for the network which is needed in order to locate the faulty line section. In addition to this, similarly to other utilization cases, basic information such as the technical specifications, age, manufacturer and model etc. can be derived from the NIS.

6 Recognition of voltage quality issues in LV network

As chapter 2 concluded, it seems that there is no reason to assume that generalizable and wide-scale problems would arise in the network due to the assessed changes. Local problems, for example at the level of individual LV feeders are, however possible. Therefore, a question of how to recognise, measure and act at such areas of interest can be asked.

In this case the increasing amount of distributed PV microgeneration and its effects on power quality are taken under assessment. According to current regulation, the customer is entitled to acquire as large microgeneration unit as he or she desires and the DSO will have to ensure its safe connectivity to grid. However, the customer is also required to inform DSO about addition of microgeneration unit to the connection point and deliver technical characteristics of the generation unit. With this information DSO can evaluate effects of the generation unit to the grid and assess the need for possible network investments.

A most probable power quality issue to be encountered with PV generation is voltage increase in LV network. For this reason a closer look to the characteristics of this phenomenon is provided, and eventually IoT based method for recognizing and managing this problem is suggested and assessed.

6.1 Voltage deviations

One of the most probable power quality issues to be encountered is the voltage increase due to photovoltaic microgeneration. The phenomenon is equivalent to voltage decrease occurring due to network load, but opposite. According to standard SFS-EN 50160 the voltage level of the distribution network should always stay within the limits of ± 10 % of the nominal voltage. [110] With distributed microgeneration in LV network it is possible that this limit will be exceeded. In fact, it has been shown that the most common limiting factor of PV generation hosting capacity in Finnish [59] and Central European distribution networks [58] is voltage increase. However, that is not always the case and determination of the limiting factor of PV hosting capacity has to be individually assessed for each LV feeding area.

The resulting voltage increase in an LV feeder is highly dependent on, among other things, the size or capacity of the microgeneration system, spatial placement of the generation in the feeder, type and dimensioning of the feeder and the voltage level in the secondary substation's busbar. [59] [111] [112] For example, generation facility that is dimensioned to be small enough to never feed power to the grid will not cause problems in voltage increase. Also, the closer to the secondary substation the generation is being connected to the LV grid, less likely it is the voltage increase will be significant [111]. The highest risk of too large voltage increases occurs in long and radial feeders with high reactance-resistance relation. [59] In practice such feeders would in most cases be old and long OHL feeders in rural and sparsely populated areas.

Instructive limitations have also been set for the momentary voltage deviation caused by individual micro generation systems connected to the grid. Finnish Energy has presented suggestive limits for networks with different voltage levels and configurations, which are presented in table 5. Essentially this means that domestic PV generation equipment should not cause voltage deviations of over 4 % while connecting to or disconnecting from standard LV grid. [114]

Table 5: *Instructive limitations for voltage deviations caused by distributed microgeneration.* [59]

Largest allowed voltage deviation	Voltage level	Connection point
2,5 %	MV	Feeder with other customer connection points
5 %	MV	Feeder with only generation connection points
4 %	LV	Any LV network with other customers
6 %	LV	Secondary substations with only generation

Due to all variables the precise determination of microgeneration's effects in the grid is not a trivial thing and simulations or calculations that take into account the specific conditions and topology of each case network have to be carried out individually. With such simulation methods usually the effects of the worst case scenario can be determined. In other words, such simulation results express a situation of maximum solar radiation when theoretical maximum power is being fed to the grid during the lowest annual self consumption and in reality such occasions can be rare and unlikely. Due to dynamic nature of solar radiation and self-consumption of the produced electricity it is possible that the limiting values achieved by simulations are never reached. Therefore, methods for measuring and tracking the changes in the network could be used to determine and assess the actual implications of PV generation in the LV network.

6.1.1 PV system characteristics and protection

According to standard SFS-EN 50438, grid connected microgeneration systems are required to be equipped with protective device that disconnect generation in case limiting values are exceeded. Protective devices need to be able to react to voltage and frequency deviations as well as loss-of-mains (LoM) situations where the distribution grid is blacked out. [113] Limiting values and required protection reaction times are presented in table 6. Usually the protection is located in the vicinity of the inverter, which means that the respective power quality measurements are done at the grid connection point of the microgeneration system.

Even though protection is able to disconnect generation from the grid when the trip settings are exceeded, there is no protection or management that would react to voltage deviation situations presented in table 5. This means that with too large PV system dimensioning the 4 % voltage deviations can be exceeded. Furthermore, even though protective devices are able to disconnect generation systems that cause

Table 6: *Finnish set-values for grid connected microgeneration's protective device. U_n is nominal voltage of the LV network.* [113]

Parameter	Clearance time	Trip setting
Over-voltage	0,2 s	U_n + 10 %
Under-voltage	0,2 s	U_n – 15 %
Over-frequency	0,2 s	51,5 Hz
Under-frequency	0,2 s	47,5 Hz
LoM	max 5 s	–

problems in the grid, it is not purposeful for neither the customer or DSO that the microgeneration systems keep continuously connecting and disconnecting from the grid. Therefore a method for continuous control over the power being fed to the grid would be beneficial.

In order to avoid unnecessary disconnections from the grid some modern PV systems are able to compensate voltage increase in the grid by adjusting power factor. In practice the PV system's inverter can detect the increasing voltage in the grid and react to it by decreasing the amount of real power being fed to the grid. However, the power factor of a microgeneration unit must be maintained between 0,9 inductive and 0,90 capacitive at all times. [113] This limits the adjustable voltage range that can be achieved with reactive power management.

6.1.2 PV generation dimensioning

Generally the determination of the possible generation capacity at each customer connection point has been done in accordance with the limit of 4 % voltage deviation introduced at table 5. In practise this is calculated with the following equation:

$$S_n = \frac{S_k}{25} \tag{1}$$

where S_n is the nominal power of the photovoltaic microgeneration unit, S_k is short-circuit power of the connection point and 25 is a factor referring to the 4 % voltage deviation limit. Short-circuit power is the only variable of the equation and it can be easily calculated from the short-circuit current I_k. Short-circuit current on the other hand is measured and documented at each customer connection point during the commissioning inspection.

This dimensioning method however, is originally developed for the use of all small scale generation and its application to distributed microgeneration has not been proven to be unambiguously effective. [114] Nevertheless, this equation is easy to use and provides at least a good estimate of the PV hosting capacity at each customer connection point. In fact, this dimensioning method is being used as basis for decisions about corrective measures to enhance local PV hosting capacity in the grid by some Finnish DSOs. [115]

6.1.3 Probable areas with power quality issues

Rauma [58] and Strandberg [59] have shown in their works that in fact the dimensioning method of using short-circuit power does not provide a reliable restricting factor of PV hosting capacity in the grid, when power quality and thermal limitations are taken into account. In simulation done in Finnish distribution network, it was found that in most cases the limiting factor of PV housing capacity is the voltage increase in LV network, while for example overloading of LV line sections played a less significant role.

Strandberg concludes that the housing capacity of PV microgeneration can be categorized according to the network area type in question. For example in city networks, it seems that power quality issues will not implement restrictions for the realizable PV housing capacity. However, in population centres, rural areas and especially in archipelago and summer cottage environment the voltage increase will usually restrict the connectable capacity of PV generation systems. [59] Derived generation capacities for each area type are presented in table 7.

Table 7: *Maximum capacity of PV generation in each connection point of the LV network when voltage increase limit is set to 10 % and 6 %.* [59]

Network area	U_n + 10 %	U_n + 6 %
City (apartment buildings)	20 kW	12 kW
City (office buildings)	>80 kW	>40 kW
Population centre	7,5 kW	5,5 kW
Rural area	6,7 kW	3,0 kW
Archipelago	2,5 kW	1,0 kW

From the results of table 7 it can be seen that especially in archipelago areas the current average PV generation capacity of approximately 5 kW has potential to cause problems in network voltage levels. However, these results have been simulated with the assumption that all customer connection points of the LV feeder are equipped with a microgeneration system of same capacity and a solar radiation data of southern Germany has been used. This decreases the achieved PV capacities. Furthermore, the simulation represents the worst case scenario, in which generation peak and annual lowest consumption occur at the same time at every connection point. [59] In practice, it is unlikely that such situations would occur, due to the dynamics of PV generation and consumption in the LV feeding area. Regardless, it is evident that large penetrations of large PV systems can cause problems especially in archipelago networks.

6.2 Measurement strategy for LV network voltages

In order to achieve a complete, detailed and real-time picture of the voltage behaviour in LV networks with large amounts of PV generation, an additional voltage measurement strategy is required. This voltage measurement system could be executed by utilizing IoT sensor based distributed voltage measurements. As previously stated in section 4.2, the current AMR meters are only able to report on severe and long-time voltage level violations from the values set by standardization. A more precise and real-time measurement system could provide more detailed information about the LV network state, which can help to understand, predict and react to voltage deviations caused by microgeneration.

As mentioned, highest areas of risk in terms of voltage swells are rural and especially archipelago networks with large amounts of PV microgeneration. Therefore the IoT based voltage metering could be primarily concentrated to such networks. With already existing customer and power quality information, identification of the most potential cites in rural and archipelago networks is already possible. However, the information is currently distributed into few different ICT systems and therefore, the identification has to be done manually. Currently the DSO's network information system is only equipped with information, whether the customer has microgeneration or not. However, this information can be utilized in locating LV feeding areas with high microgeneration concentrations. Technical specifications and for example nominal power of the generation unit can not currently be accessed through NIS and therefore, the information must be retrieved from the DSO's customer information system (CIS). The current AMR meter management system on the other hand can be utilized to retrieve power quality data of the chosen LV network, in order to for example determine whether severe voltage violations have already been encountered in the specific network and whether the microgeneration units in fact feed electricity to the grid. Meter management system can also be used to locate customers with unauthorized microgeneration.

Voltage measurements located at secondary substations are not able to produce precise enough information about the voltage behaviour throughout the whole LV network and therefore multiple distributed voltage measurement points are required. Microgeneration being fed to the grid in the middle or end part of a LV feeder can cause a local voltage increase at the vicinity of the grid connected generation, which can not be detected at the secondary substation. Therefore, the easiest and most comprehensive measurement point placement would be to install voltage measurements to each connection point with grid integrated microgeneration. This method would amount to possibly high amount of measurement points within a single feeder, depending on the installed amount of microgeneration connections, and therefore unnecessarily high costs. However, such placement would provide the most accurate and dependable measurement results.

Similarly functional measurement arrangement could however be implemented with less densely placed measurements, especially in case the number of generation connections in the feeding area is exceptionally high. In his doctoral thesis Rauma [58] suggested the use of an algorithmic method to identify the case specific amount and placement of voltage measurements needed to define the voltage behaviour of a LV network. Algorithm is based on load flow calculations done for each case network, using consumption data of lowest and highest annual power demand. This measurement schematic is able to produce a reliable picture of the voltage deviations in the network with reasonable accuracy. However, as the topologies, technical parameters and number of customers vary widely between different networks, the suggested algorithmic assessment would have to be done individually for each chosen case network. Furthermore, significant changes in consumption behaviour and installation of new microgeneration units in the network can affect negatively to the accuracy of such measurement arrangement. Anyhow, in networks with large number of customers, such placement strategy would most likely be more feasible.

As it was stated, the most probable areas in which voltage swells may occur are archipelago networks. As these areas are typically sparsely populated and consist of long and possibly old feeders with relatively few customers, it might be feasible to use the simpler method of assigning voltage measurements to each connection point with microgeneration. With low number of customers the benefit from method suggested by Rauma is limited and by assigning measurements to each generation connection the accuracy of the measurements can be ensured.

6.2.1 Requirements for IoT-based voltage measurements

Operational specifications and requirements for the measurement equipment are largely defined by the intended purpose of use. In other words, application of extracted information to the use of control measures or for determination of short voltage swell events and microgeneration protection operation times requires high performance and response times from the measurement equipment.

Installed measurements should be able to produce reliable voltage behaviour information with reasonably high accuracy and the sampling frequency of the measurements should be high enough to detect even short variations in the voltage levels. As current regulation requires the protective devices of microgeneration units to disconnect from the grid in 0,2 seconds, the measurement sampling period should be set to high enough frequency, so that the system is able to determine the realized operation times of the protection. With such sampling frequency it is also possible to produce precise enough information about the fast voltage level deviations within the $\pm$ 10 % bandwidth set by regulation. This makes it also possible to survey the instructive 4 % fast voltage deviation guideline set for grid connected microgeneration.

In terms of communication method attention should be paid on capability of transmitting relatively high amount of data with reasonably low latency, depending on whether the measurement information will be utilized in operational control measures in the network. Therefore it is possible that IoT specific wide-area-networks, such as LoRaWAN and SigFox will not be able to offer large enough bandwidth for the required data flow. These communication technologies are primarily designed to be able to transmit small amounts of data through long distances with low energy consumption. For voltage measurements the amount of data is relatively high and therefore communication methods such as 3G or LTE might have to be used.

Due to these specifications it is probable that desired metering hardware needs to be made and assembled by order and specifically tailored to meet the requirements. Overall, the equipment that can be used for operational electricity grid measurements tend not to be cheap bulk hardware which can be bought off-the-shelf. Therefore, the cost of such hardware may be higher than for example some of the sensor hardware needed for asset health applications.

6.2.2 Assessment of benefits

In the early stage, the most evident advantage from LV network voltage level measurement system is the collection and analysis of the data from networks with high microgeneration concentration. In Caruna's network there is currently no actual real-world evidence of cases where power supply from microgeneration would have caused clear voltage level increase in the distribution network. However, the current surveillance of the voltage behaviour is not very precise and based on AMR meter derived power quality event information. Therefore, it is entirely possible that short variations in voltage levels go unnoticed. Anyhow, currently the amount of microgeneration, especially in the identified risk areas of the distribution network, is still very low. With the current low penetration levels of microgeneration and lack of LV feeding areas with large generation concentrations, it is very unlikely that problems currently occur. In the scope of a decade however, problems can arise due to the rapidly increasing penetration of PV installations, projected in section 2.5.

Examples of voltage level problems can be found from other countries in Europe but as already stated, the technical limitations of Finnish networks largely differ from other European networks. Furthermore, Finnish solar radiation conditions are inferior compared to central and southern Europe. Therefore, as microgeneration further penetrates to Finnish market the metering could be used as a validation of the problem. With precise voltage level measurements it can be determined, whether the microgeneration really causes quality issues in Finnish networks. The information can be utilized to draft more precise boundary conditions for grid integration of residential PV systems and to develop better computational methods which take into account PV generation. By combining data from the voltage level measurements, AMR meter's power supply information and technical characteristics of the generation system and LV grid, a model for forecasting distributed microgeneration's grid effects could be enhanced and adjusted to Finnish conditions. Such model could later be applied to asses the housing capacities for other LV networks.

A measurement system with large sampling frequency could also be used to validate the proper operation of PV generation systems protective devices. Standard requires the microgeneration system to disconnect from the network in 0,2 s if 10 % voltage increase is detected. IoT based voltage measurement system could be used to track the realized protection operation times, in order to ensure the safety and functionality of the protection. It can be assumed that continuous connection and disconnection of generation systems is neither in DSO's or customers benefit. By calculating operation frequency of the microgeneration protection, DSO could evaluate needs for improvements in the grid. On the other hand, this information could also be used as a basis for providing consultation for the customer and for example suggesting installation of home automation or battery storage to the microgeneration system, in order to increase self-use of generation.

A measurement system with fast response time could also be utilized to implement a DSO controlled voltage control or generation curtailment system. This would require installation of an additional device to the customer's microgeneration system, which can be operated by the DSO or access to the current generation system through an API. For example, up to some point reactive power control can be used to respond to local voltage increases at the connection point of the microgeneration system. Access to such distributed voltage management equipment would enable the DSO to actively control the local voltage according to the voltage measurement system's information and further, enable the DSO to disconnect generation from the grid in case of grid maintenance, severe over voltage or LoM situation. Centralized control over distributed generation could also enable installation of larger generation capacities. In the end, the housing capacity calculations of microgeneration are usually based on worst case scenarios which are rare and unlikely, and therefore controllability of the generation systems during these rare circumstances would enable installation of larger microgeneration units which would generate more electricity for the customers during less optimal solar radiation conditions.

Overall, the measurement system would extract more detailed information about power quality issues in the network, which provides possibility for better defined reasoning in terms of investments to the grid. It enables measurement based decision making about the need for reinforcing investments. In stead of basing the investment decisions to for example on the dimensioning equation 1, decisions can be made by case specific requirements or a better and more precise estimation model can be developed.

7 Conclusion of IoT utilization

As an operational approach to IoT utilization, a method for monitoring voltage deviations in LV networks with large amount of small-scale PV generation was suggested. Assessment of chapter 2 showed that voltage increase in LV networks due to residential PV will likely be the single most significant power quality issue concerned with distributed generation. Analysis of existing power quality information shows that the available information will not necessarily be enough to determine and recognize voltage violation issues derived from grid connected PV systems. Therefore, a method based on distributed measurements throughout the network was suggested.

Even though existing grid connected PV systems are required to be equipped with protective devices, it is possible that quick voltage deviations still occur in the network. With distributed and agile voltage measurements throughout the LV network, possible quality problems can be recognized and for example, the proper operation of customer's PV system's protective devices can be measured and verified. Most importantly, the voltage measurement system can be used to first of all validate whether the PV generation actually implements voltage quality issues in Finnish conditions, and secondly, measurement system can be used to create a more precise model for simulating distributed generation's effects in network calculations and to more accurately determine PV generation housing capacities of LV networks in the future.

From the overall applicability of IoT technologies to the use of operational actions, it can be concluded that the technologies are more efficient for passively gathering information from the grid, opposed to operating as actual actuators which complete functional actions in the grid. If a component is able to functionally change or alter the operational state of the network, a SCADA integration would be required and the requirements for component and communication quality as well as information security would have to be set to a much higher level, which would compromise and complicate the easy applicability of the technology.

In this respect, application of IoT sensor devises to the use of asset health and condition monitoring applications is a more simple and resourceful approach. Monitoring schemes for circuit breakers, distribution transformers and underground cables were suggested based on application examples found from literature and the suggestions for measurement scemes for each component are presented in table 8. As the number of all chosen components in the network is very large, attention in the hardware suggestions was focused on the easy installation process and low-cost of equipment. It can also be concluded that, in case a specific site of the grid is equipped with a communication gateway hardware needed for sensor instalment and data transmission, it is most likely more feasible to install as many sensors for measurement of variable parameters at the location. Once the gateway is available, the cost of simple additional environmental measurement sensors is relatively low and therefore such measurements should be applied.

Based on this preliminary feasibility assessment it seems that circuit breaker monitoring application is the most promising in terms of achieved benefits and technical execution. The metering devices needed for CB condition monitoring can

Table 8: *Suggestion of IoT sensor based measurements needed for asset health and condition monitoring of circuit breakers, secondary substations and distribution transformers as well as underground cables.*

Circuit breakers	
Current	Motor signal current measurement
	Trip and close coils current measurement
Vibration	Substation atmospheric humidity measurement
Temperature	Control panel cabinet temperature
Humidity	Control panel cabinet humidity
Secondary substations and distribution transformers	
Temperature	Indirect transformer oil temperature measurement
	Substation atmospheric temperature measurement
Humidity	Substation atmospheric humidity measurement
Energy	Transformer load measurement
Sound	Transformer humming noise analysis
Door sensor	Substation locking verification and access control
Underground MV cables	
Current	Placement to cable terminals at secondary substations
	• High sensitivity and frequency response PD detection
	• Non-continuous measurements, few times per day
	• Exact location of fault with offline measurement

be considered to be relatively simple and low-cost. Furthermore, the gain from being able to predict and avoid CB failures can be considered to be significant, as the number of customers affected by a single CB is large. Similar monitoring arrangement implemented to CBs could also be implemented to the monitoring of remotely controlled disconnectors, which would further enhance the feasibility of such IoT application.

Similarly to CBs, the application of distribution transformer condition monitoring can be executed non-intrusively with cost efficient sensor hardware, but the achieved benefit and value of distribution transformer health monitoring can be challenging in terms of overall feasibility. However, by being able to monitor operational conditions of the whole secondary substation space, the feasibility can be increased. Benefit of such monitoring equipment could be especially feasible in special locations, such as distribution substations inside buildings, where the arrangement could be utilized to simultaneously monitor the operation of ventilation system.

Compared to other two assessed components, condition monitoring of underground cables needs to be based on more complicated measurement hardware. Most technologically feasible and reliable approach to cable monitoring seems to be utilization of online partial discharge measurements. In general, PD measurements are expensive, but by renouncing from some of the functionalities of the system, a more cost efficient method for cable condition monitoring was suggested. However, desired operation of the suggested method will still need to be validated in field conditions.

Overall it can also be stated that eventually the feasibility and achievable value from, especially asset health and condition monitoring systems, is dependent on the data management and analytics. Without a proper process for filtering and refining the raw data into usable information, the extracted data will be more or less useless and users will become overwhelmed with second grade information. Therefore, the analytics side of the system should also be paid attention to and the architecture of the data management system should be implemented in a way that easy access to the raw data can be ensured for different existing and new software systems. User application of such a system needs to be parametrized so that only necessary and relevant information will be available to the user, regardless whether the user application is an already existing or a completely new software system.

In terms of suitability of current information systems in use at Caruna, it can be stated that there is currently no system that could answer to the requirements set for such system. Current IT systems are run as individual complexes, with some APIs between them, but in order to implement wider scale IoT applications, an additional cloud-based data system would need to be implemented. It could also be worth investigating, whether such cloud based data storage could be utilized as a centralized data source for all existing information systems too. Establishment of a centralised data hub, which is used by all existing information systems would significantly enhance the usability of different data streams.

Assessment of different utilization cases in this thesis has been very general and mostly focusing on finding suitable application cases and components, as well as suggesting suitable sensors for data acquisition. The suggested cases can be concluded to be feasible in the perspective of a preliminary overall feasibility assessment and their implementation should be reasonably possible from technological point of view. However, there are a lot of aspects concerned with the different use cases that have not been thoroughly assessed in this thesis, and require further investigation. For example thorough economical assessments for the use cases need to be conducted in order to determine the economical impact and feasibility of suggested applications. Furthermore, different choices for the communication methods used in data transfer from the edge all the way to the cloud would need to be studied and evaluated. Also, even though the general architecture for a condition monitoring system has been presented, a more detailed analysis of the data storage and analysis structure would have to be implemented and execution of system integrations evaluated.

8 Summary

Objective of this thesis was to define and assess changes in energy sector which will directly or indirectly affect distribution grid operation and management in Finland, and to determine events or variables which enable identification and monitoring of the recognized changes. Based on assessment of the upcoming changes, possibilities for utilizing IoT technologies in management and monitoring applications of the identified changes were assessed. Suggestions of viable IoT based monitoring applications were presented and requirements for system architecture were made.

Changes affecting distribution networks

In the assessment of upcoming changes microgeneration, electric vehicles and heat pumps were identified to be the most probable changes to realistically penetrate to Finnish energy sector within a time scope of approximately 10 years. In addition to those, demand response, energy communities, asset health monitoring and security of supply investments were assessed.

Security of supply investments, in which majority of Caruna's MV and LV overhead line network will be replaced with underground cables, are already well on their way and the most evident effects will be realized as improved reliability of electricity supply. However, simultaneously the capacity of the network will increase and possibilities for manual and remotely controlled operational switching will significantly increase. Therefore the ongoing investments ease the integration and management of other upcoming changes in the network.

Penetration of microgeneration, mostly residential PV has more or less doubled annually during last few years, and the development can be expected to continue at a similar rate. However, with realistic penetration forecasts the congestions in network component loading and reverse power flows in the grid can be considered to be unlikely in a wider scale. The most likely complication derived from increasing penetration of residential PV penetration is voltage increase in rural and archipelago LV networks. However, even such problems can not be expected to appear systematically, and the appearance of voltage quality problems is very case specific.

Penetration of electric vehicles to the Finnish car stock can be expected to significantly increase in the future, but in respect to the size of the car fleet, the penetration will remain modest during the next decade. With projected penetration percentage of 4–8 % the impact of EV charging to the distribution network load levels are not likely to widely increase to problematic levels, even without smart charging. Single biggest load increase in the network will occur at distribution transformers, where the load level increases 0–2 % with the projected EV penetrations. Issues in individual LV networks and problems with power quality can be possible but application of smart charging of EVs will largely reduce their probability.

During the last decade, amount of heat pumps has rapidly increased and similar growth rate can be expected to continue. Clear majority of new HP investments are air heat pumps, which are mostly used for substituting direct electric heating, while ground source heat pumps are the second most popular technology with clearly smaller equity of the market. In general, air heat pumps can be considered to decrease and ground source heat pumps to increase network loads. In the end it is possible that as the two technologies compensate each other, an equilibrium will settle near to a neutral load effect on a wide scale but individual problems may occur in LV networks with high GHP concentrations. Power quality issues on the other hand can be encountered during start-up of large pumps, but they can be avoided by using 3-phased connections and slow start functionalities.

Demand response can be considered to be a fairly probable part of the power system in the near future. However, the actual implementation and final characteristics are currently largely undefined which complicates the assessment of the possible challenges it introduces. Type and scale of the impact DR imposes is eventually strongly dependent on the final structure and execution of the system. It has for example been shown that if SPOT market or reserve market signals are used as load control signals, peak load levels of the distribution networks will increase. To compensate such DR systems effects, power based distribution tariff structures are widely suggested.

Asset health and condition monitoring is a field that has significantly increased its feasibility mostly due to the technological and economical development of computing and electronic hardware. It is likely that it will further secure its foothold in distribution networks as applications of IoT develops. Continuous health monitoring of critical grid components can enable detection of upcoming component malfunctions and network faults, therefore providing possibility to act in advance, improving security of supply and decreasing repair costs. Additionally, it enables allocation of maintenance programs according to the actual need instead of time-based inspections.

Residential electrical energy storages will keep penetrating to Finnish households mostly due to increasing amount of residential PV generation. Overall, the introduction of electricity storages can be seen as a positive change from the technical perspective of the distribution grid. While used as a part of residential solar electricity system to increase the self-use of PV generation, the positive effect of battery storages is most evident, as the amount of surplus electricity being fed to the grid can be decreased. Similarly application of battery storage to residential scale peak-shaving of electricity consumption will slightly decrease the load stress of the distribution network. Final penetration of electrical energy storages in Finnish households will remain to be seen and it is largely impacted by for example economical development of battery technologies.

Generalisation of energy communities in power system will remain to be seen and is largely dependent on the development of regulative aspects. Most probable development direction for energy communities is emergence of communes or groups of customers which are allowed to freely use and exchange self generated electricity from individual or commonly owned microgeneration facilities. In such case the effect of energy communities to the distribution grid will be close to the effects derived from residential PV generation systems equipped with battery storages. Due to larger amount of individual customers to consume the generated electricity, the amount of electricity being fed to the grid can be expected to be relatively small. In general the technical problems caused by energy communities will most likely remain marginal.

Overall, none of the changes stand out as a source of evident problems in the distribution network. It seems that the state of Finnish grid infrastructure is so good that at least individually, the predicted changes in the power system will have only little effect even with over ambitious assumptions of penetration levels of different technologies. Taking into account the unified effects of all the changes, it is possible that for example load increases can cumulate to produce higher power peaks in the system, but still in terms of the limitations of the grid, the encountered change will likely not cause any general or systematic problems. Similarly there seems to be no reason to assume any systematic issues in terms of power quality or network protection. However, this does not exclude the fact that local problems, for example at the level of individual LV networks can be encountered.

Utilization of IoT technologies

Based on the assessment of changes it seems that there is no reason to assume that generalizable and wide-scale problems would arise in the distribution network and therefore focus of the possible IoT utilization cases were focused to improving existing processes and identification and verification of local complications caused by the assessed changes. Therefore, methods for applying asset health and condition monitoring to chosen network components as well as possibilities for identifying power quality problems caused by residential PV generation were assessed and suggested. Furthermore, requirements and possibilities of designing data management and analysis systems for introduction of IoT sensor based measurements were evaluated.

In terms of suitability of current information systems in use at Caruna, it was stated that there is currently no system that could answer to the requirements set for IoT applications and in order to apply IoT sensors to the network an additional platform would need to be established. Current IT systems are run as individual complexes, responsible for specific tasks or fields of applications, with little interconnections between them. It could be worth investigating, whether establishment of a centralised data hub, which is used by all existing information systems would be possible, as it would significantly enhance the usability of data streams from all existing information and data sources.

For a more operational approach to IoT utilization a system for measuring voltage deviations caused by residential PV generation was assessed. Even though existing grid connected PV systems are required to be equipped with protective devices, it is possible that quick voltage deviations still occur in the network. With distributed and agile voltage measurements throughout the LV network, possible quality problems can be recognized and for example, the proper operation of customer's PV system's protective devices can be measured and verified. Most importantly, the voltage measurement system can be used to first of all validate whether the PV generation actually implements voltage quality issues in Finnish conditions, and secondly, measurement system can be used to create a more precise model for simulating distributed generation's effects in network calculations and to more accurately determine PV generation housing capacities of LV networks in the future.

From the overall applicability of IoT technologies to the use of operational actions, it can be concluded that the technologies are more efficient for passively gathering information from the grid, opposed to operating as actual actuators which complete functional actions in the grid. Applications which passively gather data from the grid and are not required to complete any operational switching activities and can be implemented more easily, as for example their functionality cybersecurity are less critical.

In this respect it was stated that applications focusing on asset health and condition monitoring would be more feasible and easily implementable. Total of three cases were assessed for different components including: circuit breakers, underground cables as well as combination of secondary substations and distribution transformers. Suggestions of measurements needed for determination of operational health or condition were made for each chosen component. Based on the assessment it was concluded that of the three alternatives circuit breaker monitoring is the most promising application in terms of achieved benefits and technical execution.

For asset health and condition monitoring application of CBs, an IoT sensor based measurements of current, vibration, temperature and humidity were suggested. Therefore the sensor, equipment needed for CB condition monitoring can be considered to be relatively simple and low-cost. Combination of the measurement parameters with existing component data from information systems would enable determination of components operational condition and expected lifespan. Furthermore, the gain from being able to predict and avoid CB failures can be considered to be significant, as the number of customers affected by a single CB is large.

For condition monitoring of secondary substations and distribution transformers a combination of atmospheric measurements in the substation cabin space and measurements of transformer operation was suggested. Transformer load could be measures with energy measurements, oil temperature and cabin air temperature with a set of temperature sensors and humming noise of the transformer could be monitored with microphones. Furthermore, humidity of the space and fastening of the cabin door could be derived with additional sensors. Such arrangement would enable monitoring of transformer operation as well as operational conditions and safety of the technical space.

Monitoring of underground cables is more complex compared to the two other suggestions and sets higher requirements for sensor hardware, communication and analytics. Most technologically feasible and reliable approach to cable monitoring seems to be utilization of online partial discharge measurements. In general, PD measurements are expensive, but by renouncing from some of the functionalities of the system, a more cost efficient method for cable condition monitoring was suggested. With pairs of fast response current measurement at opposite end of a line section presence of PD measurements in the corresponding cable section can be recognized.

Overall, the suggested monitoring cases were determined to be all technically feasible in the preliminary assessment. However, in order to further validate the application cases, a more thorough assessment about for example economical feasibility of the suggested cases would need to be conducted. Furthermore, the suggestions of this thesis mostly focused on sensor and measurement choices for different cases and therefore communication methods for actual implementation would need to be assessed. Also, an evaluation about the realization of the IoT platform for gathering and analysis of the data should be conducted.

References

[1] Heuveldop, N. "Ericsson mobility report" [online]. Report. Ericsson AB. June, 2017. [cited 1.9.2017]. Available at: https://www.ericsson.com/assets/local/mobility-report/documents/2017/ericsson-mobility-report-june-2017.pdf.

[2] Electricity Market Act. 9.8.2013/588. Ministery of Economic Affairs and Emplotyment. Finland.

[3] Heywood, R. J. and McGrail, T. "Clarifying the link between data, diagnosis and Asset Health Indices" [online]. Conference paper. Asset Management Conference, 2015. [cited 14.11.2017.] Available at: https://doi.org/10.1049/cp.2015.1748.

[4] Li, S., Li, J. "Condition monitoring and diagnosis of power equipment: review and prospective" [online]. IET, *High Voltage*, 2:2, 2017. [cited 22.11.2017.] Available at: https://doi.org/10.1049/hve.2017.0026.

[5] Luojus, M. "Reactive Power Compensation Strategy in Distribution Network". MSc. Thesis. Aalto University, Department of Electrical Engineering. 2017.

[6] Korkka, M. "Keskijänniteverkon maasulkuvirtojen kompensointi verkon korvaustilanteissa". MSc. Thesis. Aalto University, Department of Electrical Engineering. 2016.

[7] Fingrid Oyj. "Loissähkön käyttö ja loistehoreservi". [web page]. 2016. [cited 17.11.2017] Available at: http://www.fingrid.fi/fi/asiakkaat/Kantaverkkopalvelut/loissahko/Sivut/default.aspx

[8] Finnish Standard Association SFS. "SFS 6001 High-voltage electrical installations". SESKO Standardisation in Finland, 4th edition, 2015.

[9] International Energy Agency. "Global EV Outlook 2016" [online]. Paris, France, 2016. [cited 6.9.2017]. Available at: https://www.iea.org/publications/freepublications/publication/Global_EV_Outlook_2016.pdf

[10] International Energy Agency. Transport, "Energy and CO2: Moving towards Sustainability" [online]. Paris, France, 2009. [cited 6.9.2017]. Available at: https://www.iea.org/publications/freepublications/publication/transport2009.pdf

[11] International Energy Agency. "Tracking Clean Energy Progress 2017" [online]. Paris, France, 2017. [cited 6.9.2017]. Available at: https://www.iea.org/publications/freepublications/publication/TrackingCleanEnergyProgress2017.pdf

[12] Liikenneturvallisuusvirasto Trafi. Liikennekäytössä olevat sähköautot. [web page]. Updated 30.6.2017. [cited 6.9.2017]. Available at: https://www.trafi.fi/tietopalvelut/tilastot/tieliikenne/ajoneuvokanta/ajoneuvokannan_kayttovoimatilastot/sahkokayttoiset_autot.

[13] VTT Technical Research Center of Finland. "ALIISA autokantamalli" [web page]. VTT, Lipasto database. 2016. [cited 8.9.2017]. Available at: http://www.lipasto.vtt.fi/aliisa/index.htm.

[14] Huttunen, R. "Government report on the National Energy and Climate Strategy for 2030" [online]. *Publications of the Ministry of Economic Affairs and Employment 4/2017*. Ministry of Economic Affairs and Employment. 2017. [cited 6.9.2017]. Available at: http://urn.fi/URN:ISBN:978-952-327-190-6

[15] International Electrotechnical Commission. "IEC 61851-1:2017 Electric vehicle conductive charging system - Part 1: General requirements". Edition 3.0. 2017.

[16] SESKO SK 69. "Sähköajoneuvojen lataaminen kiinteistöjen sähköverkoissa" [online]. National recommendation. SESKO ry. 2015. [cited 12.9.2017]. Available at: http://www.sesko.fi/files/431/Lataussuositus_2014_2015-07-13.pdf.

[17] Vesa, J. "Presentation about electric vehicle standards" [online]. SESKO ry. 2016. [cited 12.9.2017]. Available at: http://www.sesko.fi/files/671/EV-charging_standards_may2016_Compatibility_Mode_.pdf.

[18] Energiateollisuus ry. "Energiavuosi 2016". Report. [online]. 2017. [cited 18.9.2017]. Available at: https://energia.fi/ajankohtaista_ja_materiaalipankki/materiaalipankki/energiavuosi_2016_-_sahko.html.

[19] Alahäivälä, A. "Sähköautojen lataaminen ja sen vaikutus kaupunkialueen jakelumuuntajiin". MSc. Thesis. Aalto University, Department of Electrical Engineering. 2012.

[20] Rautiainen, A. "Aspects of Electric Vehicles and Demand Response in Electricity Grids". Doctoral thesis. Publication; Vol. 1327. Tampere University of Technology. 2015.

[21] Tuunanen, J. "Modelling of changes in electricity end-use and impacts on electricity distribution". Doctoral thesis. Lappeenranta University of Technology. 2015.

[22] Koreneff, G et al. "Future development trends in electricity demand" [online]. Report. VTT Technical Research Center of Finland. 2009. [cited 19.9.2017] Available at: http://www.vtt.fi/inf/pdf/tiedotteet/2009/T2470.pdf

[23] Yurdakul, Ü. "Sähköautojen latausverkon yleissuunnittelu". MSc. Thesis. Aalto University, Department of Electrical Engineering. 2013.

[24] Unkuri, A." Sähköautojen vaikutukset kaupungin sähkönjakeluverkkoon". MSc. Thesis. Tampere University of Technology, Department of Electrical Engineering. 2011.

[25] A. Tammi. "Effects of plug-in vehicles in distribution network and business". MSc. Thesis. Tampere University of Technology, Department of Electrical Engineering. 2011.

[26] Shahnia, F., et al. "Voltage unbalance sensitivity analysis of plug-in electric vehicles in distribution networks" [online]. *Power Engineering Conference (AUPEC), 2011 21st Australasian Universities.* [cited 27.9.2017] IEEE. 2011. Available at: https://www.researchgate.net/publication/241625067.

[27] Finnish Heat Pump Association (SULPU). Ilmalämpöpumppu (ILP) [web page]. [cited 29.9.2017]. Available at: https://www.sulpu.fi/ilmalampopumppu.

[28] Finnish Heat Pump Association (SULPU). "Myydyt lämpöpumput 2016" [online]. 2016. [cited 29.9.2017]. Available at: https://www.sulpu.fi/documents/184029/208772/Myydyt%20l%C3%A4mp%C3%B6pumput%202016%2C%20kaaviot%2C%20f.pdf.

[29] Suomen virallinen tilasto (SVT). "Asumisen energiankulutus" [online]. Statistics Finland, Helsinki. [cited 2.10.2017]. Available at: http://www.stat.fi/til/asen/

[30] Gaia Consulting Oy. "Lämpöpumppuinvestointien alue- ja kansantaloudellinen tarkastelu" [online]. Finnish Heat Pump Association (SULPU). 2014. [cited 2.10.2017]. Available at: https://www.sulpu.fi/documents/184029/209175/L%C3%A4mp%C3%B6pumppuinvestointien%20alue-%20ja%20kansantaloudellinen%20tarkastelu%20-%20raportti.pdf

[31] Finnish Heat Pump Association (SULPU). "Lämpöpumpputilasto 2016" [online]. 2016. [cited 2.10.2017]. Available at: https://www.sulpu.fi/documents/184029/208772/SULPU%2C%20myydyt%20l%C3%A4mp%C3%B6pumput%202016%2C%20teholuokittain%2C%20f.pdf.

[32] Lovio, R. "Kommentteja Suomen energia- ja ilmastotiekartan 2050 valmisteluun" [online]. 15th Anniversary Seminar of SULPU. 2014. [cited 2.10.2017]. Available at: https://www.sulpu.fi/documents/184029/2220831/2-Raimo%20Lovio%2C%20%20Aalto%20-%20Professoriryhm%C3%A4-%20L%C3%A4hienergialiitto.pdf.

[33] Navarro-Espinosa, A. and Mancarella, P. "Probabilistic modeling and assessment of the impact of electric heat pumps on low voltage distribution networks" [online]. *Applied Energy*, 2014, 127: 249-266. [cited 5.10.2017]. Available at: https://doi.org/10.1016/j.apenergy.2014.04.026

[34] Asare-Bediako, B., Kling, W. L. and Ribeiro, P. F. "Future residential load profiles: Scenario-based analysis of high penetration of heavy loads and distributed generation" [online]. *Energy and Buildings*, 2014, 75: 228-238. [cited 5.10.2017]. Available at: https://doi.org/10.1016/j.enbuild.2014.02.025

[35] Hagström, M., Pesola, A. "Lämpöpumppujen vaikutukset sähkötehon tarpeeseen" [online]. Finnish Heat Pump Association (SULPU), Gaia Consulting Oy. 2017. [cited 2.10.2017]. Available at: https://www.sulpu.fi/documents/184029/0/L%C3%A4mp%C3%B6pumppujen%20vaikutukset%20s%C3%A4hk%C3%B6tehon%20tarpeeseen%20-%20Loppuraportti%20FINAL%204-2017%20%28ID%2029764%29.pdf.

[36] Tuunanen, J. "Lämpöpumppujen vaikutukset sähköverkkoliiketoiminnan kannalta". MSc. Thesis. Lappeenranta University of Technology, Department of Electrical Engineering. 2009.

[37] Tiuraniemi, J. "Alueellinen sähkökuormien kehitysennuste Rovaniemen Verkko Oy:n jakelualueella". MSc. Thesis. Lappeenranta University of Technology, Department of Electrical Engineering. 2016.

[38] Finnish Energy. "Periaatteita vika- ja häiriötilanteiden selvittämiseksi". Memorandum [online]. 2008. [cited 2.10.2017] Available at: http://188.117.57.25/sites/default/files/periaatteita_vikatilanteiden_selvittamiseksi_121108.pdf.

[39] Syrjäsalo, N. "Maalämpöpumppujen käynnistysten verkkovaikutukset". Final Thesis. Tampere University of Applied Sciences, Department of electrical engineering. 2013.

[40] International Electrotechnical Commision. "Electrical Energy Storage" [online]. White Paper. Geneve, Switzerland. 2011. [cited 10.10.2017] Available at: http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf

[41] Hoppmann, J., et al. "The economic viability of battery storage for residential solar photovoltaic systems – A review and a simulation model" [online]. *Renewable and Sustainable Energy Reviews*, 2014, 39:1101-1118. Available at: https://doi.org/10.1016/j.pnsc.2008.07.014

[42] Agnew, S. and Dargush, P. "Consumer preferences for household-level battery energy storage" [online]. *Renewable and Sustainable Energy Reviews*. 75:609–617, 2017. [cited 11.10.2017]. Available at: http://dx.doi.org/10.1016/j.rser.2016.11.030

[43] Hassan, A. S., Cipcigan, L. and Jenkins, N. "Optimal battery storage operation for PV systems with tariff incentives" [online]. *Applied Energy*. 203:422–441, 2017. [cited 11.10.2017]. Available at: https://doi.org/10.1016/j.apenergy.2017.06.043

[44] Lassila, J., et al. "Methodology to Analyze the Economic Effects of Electric Cars as Energy Storages" [online]. *IEEE Transactions on Smart Grid.* 3:506-516, 2011. [cited 11.10.2017]. Available at: 10.1109/TSG.2011.2168548

[45] Olaszi, B. D., Ladanyi, J. "Comparison of different discharge strategies of grid-connected residential PV systems with energy storage in perspective of optimal battery energy storage system sizing" [online]. *Renewable and Sustainable Energy Reviews.* 75:710-718, 2017. [cited 13.10.2017]. Available at: http://dx.doi.org/10.1016/j.rser.2016.11.046

[46] Finnish Energy. "Hajautettua sähkön pientuotantoa" [online]. Webpage. [cited 16.10.2017]. Available at: https://energia.fi/perustietoa_energia-alasta/asiakkaat/sahkoasiakkuus/sahkon_pientuotanto

[47] Partanen, J. "Älykäs sähköverkko ja pientuotanto" [online]. *Aurinkoinen pintuotanto seminar.* 2017. [cited 16.10.2017]. Available at: https://energia.fi/files/1451/Pientuotanto_ja_alykas_sahkoverkko.pptx

[48] Gaia Consulting Oy. "Sähkön pientuotannon kilpailukyvyn ja kokonaistaloudellisten hyötyjen analyysi" [online]. Report. 2014. [cited 17.10.2017]. Available at: http://docplayer.fi/671154-Sahkon-pientuotannon-kilpailukyvyn-ja-kokonaistaloudellisten-hyotyjen-analyysi.html

[49] Finnish Energy Authority. "Sähköverkkoon kytketty aurinkosähkökapasiteetti yli kolminkertaistui vuodessa" [online]. Press release. 2017. [cited 16.10.2017]. Available at: https://www.energiavirasto.fi/-/sahkoverkkoon-kytketty-aurinkosahkokapasiteetti-yli-kolminkertaistui-vuodessa

[50] Remme, U. "Solar PV Vision by 2015" [online]. International Energy Agency, Energy Technology Policy Division. 2014. [cited 17.10.2017]. Available at: https://www.iea.org/media/workshops/2014/solarelectricity/RemmePVVisionforWeb.pdf

[51] Sorsanen, J. "Realistisen aurinkosähkön tuotantopotentiaalin evaluointi verkkoonkytketyille aurinkosähköjärjestelmille Tapiolan aluella". MSc. Thesis. Aalto University, Department of Electrical Engineering. 2015.

[52] Hakkarainen, T., et al. "The role and opportunities for solar energy in Finland and Europe" [online]. VTT Technical Research Center of Finland. 2015. [cited 18.10.2017]. Available at: http://www.vtt.fi/inf/pdf/technology/2015/T217.pdf.

[53] Rexel Finland Oy. "Aurinkosähköjärjestelmät: Helpot aurinkosähköjärjestelmät kiinteistöihin" [online]. [cited 18.10.2017]. Available at: http://www.vtt.fi/inf/pdf/technology/2015/T217.pdf.

[54] Airaksinen, M., et al. "Rakennetun ympäristön hajautetut energiajärjestelmät" [online]. Report. Suomen ilmastopaneeli. 2013. [cited 19.10.2017]. Available

at: http://www.ilmastopaneeli.fi/uploads/selvitykset_lausunnot/Rakennetun%20ymp%C3%A4ris%C3%B6n%20hajautetut%20energiaj%C3%A4rjestelm%C3%A4t.pdf.

[55] Ugalde, C. and Jenkins, N. "Future GB Power System Stability Challenges and Modelling Requirements" [online]. The Institution of Engineering & Technology. 2015. [cited 19.10.2017]. Available at: http://www.theiet.org/sectors/energy/documents/modelling-12.cfm?type=pdf.

[56] Ketterer, J. C. "The impact of wind power generation on the electricity price in Germany" [online]. *Energy Economics*, 44:270–280, 2014. [cited 19.10.2017]. Available at: https://doi.org/10.1016/j.eneco.2014.04.003.

[57] Lassila, J., et al. "Nationwide Photovoltaic Hosting Capacity in the Finnish Electricity Distribution System" [online]. Conference Paper. *32nd European Photovoltaic Solar Energy Conference*. 2016. [cited 24.10.2017]. Available at: https://www.researchgate.net/publication/304379758_Nationwide_Photovoltaic_Hosting_Capacity_in_the_Finnish_Electricity_Distribution_System.

[58] Rauma, K. "Industrial Aspects of Voltage Management and Hosting Capacity of Photovoltaic Power Generation in Low Voltage Networks". Doctoral Thesis. Université Grenoble Alpes, 2016.

[59] Strandberg, J. "Pientuotannon liittäminen sähkönjakeluverkkoon, teknillinen tarkastelu". MSc. Thesis. Aalto University, School of Electrical endineering, Department of Electrical Engineering and Automation, 2016.

[60] Lehto, I. "Ohje verkon suunnittelijoille tuotannon liittämisestä" [online]. Technical instruction. Finnish Energy, 2016. Available at: http://188.117.57.25/sites/default/files/ohje_verkon_suunnittelun_tueksi.pdf

[61] Alahaivala, A. "Harnessing Demand Response for Power System Flexibility". Doctoral thesis. Aalto University, Department of Electrical Engineering and Automation, 2017.

[62] Järventausta, P., et al. "Kysynnän jousto – Suomeen soveltuvat käytännön ratkaisut ja vaikutukset verkkoyhtiöille (DR pooli)" [online]. Report. Tampere University of Technology, Department of electrical engineering, 2015. [cited 30.10.2017]. Available at: https://tutcris.tut.fi/portal/files/4776899/kysynnan_jousto_loppuraportti.pdf

[63] Älyverkkotyöryhmä. "Älyverkkovisio" [online]. Ministry of Economic Affairs and Employment, 2016. [cited 1.11.2017]. Available at: http://tem.fi/documents/1410877/3481825/%C3%84lyverkkovisio+final/9ddc2545-586e-4574-8195-ef9987a07151.

[64] Koponen, P., et al. "Markkinahintasignaaleihin perustuva pienkuluttajien sähkönkäytön ohjaus" [online]. Report. VTT Technical Research Center of Finland, 2006. [cited 1.11.2017]. Available at: http://www.vtt.fi/inf/pdf/tiedotteet/2006/T2362.pdf

[65] Honkapuro, S., et al. "Jakeluverkon tariffirakenteen kehitysmahdollisuudet ja vaikutukset" [online]. Report. Lappeenranta University of Technology and Tampere University of Technology, 2017. [cited 31.10.2017]. Available at: https://energia.fi/files/1712/Jakeluverkon_tariffirakenteen_kehitysmahdollisuudet_ja_vaikutukset_-loppuraportti_LUT_TUT_20170818.pdf

[66] Älyverkkotyöryhmä. "Matkalla kohti joustavaa ja asiakaskeskeistä sähköjärjestelmää" [online]. Report. Ministry of Economic Affairs and Employment, 2017. [cited 3.11.2017]. Available at: http://tem.fi/artikkeli/-/asset_publisher/alyverkkotyoryhman-valiraportti-matkalla-kohti-joustavaa-ja-asiakaskeskeista-sahkojarjestelmaa.

[67] Mutanen, A., et al. "Customer Classification and Load Profiling Method for Distribution Systems" [online]. *IEEE Transactions on Power Delivery*, 26:3, 2011. [cited 6.11.2017]. Available at: https://doi.org/10.1109/TPWRD.2011.2142198

[68] Diamantoulakis, P., Kapinas, V. and Karagiannidis, G. "Big Data Analytics for Dynamic Energy Management in Smart Grids" [online]. *Big Data Research*, 2:94-101, 2015. [cited 9.11.2017]. Available at: https://doi.org/10.1016/j.bdr.2015.03.003

[69] Kialashaki, A., Reisel, J. "Modeling of the energy demand of the residential sector in the United States using regression models and artificial neural networks" [online]. *Applied Energy*, 108:271-280, 2013. [cited 9.11.2017]. Available at: http://dx.doi.org/10.1016/j.apenergy.2013.03.034

[70] Nanpeng, Y., et al. "Big Data Analytics in Power Distribution Systems" [online]. Conference paper. Innovative Smart Grid Technologies Conference (ISGT), IEEE Power & Energy Society, 2015. [cited 8.11.2017]. Available at: https://doi.org/10.1109/ISGT.2015.7131868

[71] Finnish Energy Autrhority. "Regualtion Methods 2016 - 2023" [online]. 2015. [cited 8.11.2017]. Available at: https://www.energiavirasto.fi/documents/10191/0/Appendix_2_Regulation_methods_DSOs_2016-2023.pdf/b298b19e-04dc-4779-ab73-a709444bdace

[72] Dehghanian, P., et al. "Critical Component Identification in Reliability Centered Asset Management of Power Distribution Systems Via Fuzzy AHP" [online]. *IEEE Systems Journal*, 6:4, 2012. [cited 13.11.2017.] Available at: https://doi.org/10.1109/JSYST.2011.2177134.

[73] Rhein, A., et al. "Multi-criteria Optimization of Maintenance and Replacement Strategies in Transmission Systems" [online]. Conference paper. Probabilistic Methods Applied to Power Systems (PMAPS), International Conference, 2016 . [cited 13.11.2017.] Available at: https://doi.org/10.1109/PMAPS.2016.7764140.

[74] Tragoonthai, S. and Chaitusaney, S. "Optimal Budget Allocation for Preventive Maintenance of Distribution System Considering Outage Cost and Reliability Indices" [online]. Conference paper. 14th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON), 2017. [cited 13.11.2017.] Available at: https://doi.org/10.1109/ECTICon.2017.8096309.

[75] Wolf, G. "Asset Health Awareness Changing the Grid" [webpage]. Penton, T&DWorld, 2017. [cited 14.11.2017.] Available at: http://www.tdworld.com/asset-managementservice/asset-health-awareness-changing-grid

[76] Mobley, R. K. "An introduction to Preventive Maintenance", 2nd edition [e-book]. Butterworth-Heinemann, Boston, MA, 2002.

[77] Hosein, P., Hosein, S. and Bahadoorsingh, S. "Power Grid Fault Detection using an AMR Network" [online]. Conference paper. Innovative Smart Grid Technologies - Asia (ISGT ASIA), 2015 IEEE. [cited 14.11.2017.] Available at: https://doi.org/10.1109/ISGT-Asia.2015.7387008.

[78] Auvinen, K., et al. "FinSolar: Aurinkoenergian markkinat kasvuun Suomessa" [online]. Report. *KAUPPA + TALOUS*, 1/2016, Aalto University. [cited 4.12.2017.] Available at: https://aaltodoc.aalto.fi/bitstream/handle/123456789/20264/isbn9789526067674.pdf?sequence=1&isAllowed=y.

[79] Seppä, H. "Onko esineiden internet oikeasti palveluiden internet?" [online]. Blog text. *VTT Blog*, VTT Technical Research Centre of Finland. [cited 12.12.2017.] Available at: https://vttblog.com/2017/06/22/onko-esineiden-internet-palveluiden-internet/.

[80] Cisco Systems Inc. "The Zettabyte Era: Trends and Analysis" [online]. White Paper. [cited 14.12.2017.] Available at: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/vni-hyperconnectivity-wp.html.

[81] Meulen, R. "Gartner Says 8.4 Billion Connected "Things" Will Be in Use in 2017, Up 31 Percent From 2016" [online]. Press release. [cited 14.12.2017.] Available at: https://www.gartner.com/newsroom/id/3598917.

[82] Yaqoob, I., et al. "Internet of Things Architecture: Recent Advances, Taxonomy, Requirements, and Open Challenges" [online]. *IEEE Wireless Communications*, 24:3, 2017. [cited 13.12.2017.] Available at: https://doi.org/10.1109/MWC.2017.1600421.

[83] Gubbi, J., et al. "Internet of Things (IoT): A vision, architectural elements, and future directions" [online]. *Future Generation Computer Systems*, 29:7, 2013. [cited 14.12.2017.] Available at: https://doi.org/10.1016/j.future.2013.01.010.

[84] Lopez Research LLC. "An Introduction to the Internet of Things (IoT)" [online]. Report. 2013. [cited 14.12.2017.] Available at: https://www.cisco.com/c/dam/en_us/solutions/trends/iot/introduction_to_IoT_november.pdf.

[85] Lee, I. and Lee, K. "The Internet of Things (IoT): Applications, investments, and challenges for enterprises" [online]. *Business Horizons*, 58:4, 2015. [cited 14.12.2017.] Available at: https://doi.org/10.1016/j.bushor.2015.03.008.

[86] Borgia, E. "The Internet of Things vision: Key features, applications and open issues" [online]. *Computer Communications*, 54, 2014. [cited 14.12.2017.] Available at: https://doi.org/10.1016/j.comcom.2014.09.008.

[87] Alibaba Group. "DHT21 Capacitive Proximity Sensor Temperature Humidity Sensor" [online]. Web page. Shenzhen ZKP Intelligent technology Co. 2018. [cited 6.2.2018.] Available at: https://www.alibaba.com/product-detail/New-Product-DHT21-Capacitive-Proximity-Sensor_60367880957.html?spm=a2700.7724838.2017115.106.63bc82aepXwoDR.

[88] Messer, A. "Sound analysis: Best practices for condition monitoring using ultrasound" [online]. UE Systems. *Plant Services*, 2015. [cited 6.2.2018.] Available at: https://www.plantservices.com/articles/2015/best-practices-condition-monitoring-using-ultrasound/?show=all.

[89] Vaattovaara, M. Vice President, Domestic sales, ABB Oy. Interview. 4.1.2018.

[90] Rudd, S. E. et. al. "Circuit Breaker Prognostics Using SF6 Data" [online]. Conference paper. IEEE power and energy society general meeting. IEEE Power and Energy Society General Meeting PESGM. 2011. [cited 9.2.2018.] Available at: https://strathprints.strath.ac.uk/37466/1/SRudd_paper.pdf.

[91] Razi-Kazemi, A. A., et. al. "Circuit-Breaker Automated Failure Tracking Based on Coil Current Signature" [online]. *IEEE Transactions on Power Delivery,* 29:1, 2014. [cited 13.2.2018.] Available at: https://doi.org/10.1109/TPWRD.2013.2276630.

[92] Melli, et. al. "Design of Online Circuit Breaker Condition Monitoring Hardware" [online]. Conference paper. 2nd International Conference on Control, Instrumentation and Automation (ICCIA), 2011. [cited 13.2.2018.] Available at: https://doi.org/10.1109/ICCIAutom.2011.6356751.

[93] Melli, et. al. "Design of Online Circuit Breaker Condition Monitoring Hardware" [online]. Conference paper. 2nd International Conference on Control, Instrumentation and Automation (ICCIA), 2011. [cited 13.2.2018.] Available at: https://doi.org/10.1109/ICCIAutom.2011.6356751.

[94] Feizifar, B. and Usta, O. "Condition Monitoring of Circuit Breakers: Current Status and Future Trends" [online]. Conference paper. IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe), 2017. [cited 13.2.2018.] Available at: https://doi.org/10.1109/EEEIC.2017.7977751.

[95] Hoidalen, H. K. and Runde, M. "Continuous Monitoring of Circuit Breakers Using Vibration Analysis" [online]. *IEEE Transactions on Power Delivery,* 20:4, 2005. [cited 13.2.2018.] Available at: https://doi.org/10.1109/TPWRD.2005.855486.

[96] Saksela, K. CEO, Noiseless Acoustics Ltd. Interview. 16.1.2018.

[97] Singh, J. "Condition Monitoring of Power Transformer - Bibliography Survey 2" [online]. *International Journal of Engineering Science Invention Research & Development,* 3:3, 2016. [cited 15.2.2018.] Available at: http://www.ijesird.com/september_2_16.PDF.

[98] Montanari, C. G., Morshius, P. and Cervi, A. "Monitoring HV transformer conditions: the strength of combining various diagnostic property observations" [online]. Conference paper. Electrical Insulation Conference (EIC), Seattle, Washington, USA, 2015. [cited 15.2.2018.] Available at: https://doi.org/10.1109/ICACACT.2014.7223590.

[99] Han, Y. and Song, Y. H. "Condition Monitoring Techniques for Electrical Equipment — A Literature Survey" [online]. *IEEE Transactions on Power Delivery,* 18:1, 2003. [cited 15.2.2018.] Available at: https://doi.org/10.1109/TPWRD.2002.801425.

[100] Zhang, X. and Gockenbach, E. "Asset-Management of Transformers Based on Condition Monitoring and Standard Diagnosis" [online]. *IEEE Electrical Insulation Magazine,* 24:4, 2008. [cited 16.2.2018.] Available at: https://doi.org/10.1109/MEI.2008.4581371.

[101] McArthur, S., Strachan, S. and Jahn, G. "The Design of a Multi-Agent Transformer Condition Monitoring System" [online]. *IEEE Transactions on Power Delivery,* 19:4, 2004. [cited 16.2.2018.] Available at: https://doi.org/10.1109/TPWRS.2004.835667.

[102] Volanen, V. "Comparison of Caruna's and Electricity North West Limited's business areas and evaluation of suitability of Electricty North West Limited's preselected Research and Development Projects for Caruna". MSc. Thesis. Lappeenranta University of Technology, LUT School of Energy Systems. 2017.

[103] Avinash, N. A. et. al. "Remote Condition Monitoring System for Distribution Transformer" [online]. Conference paper. Power Systems Conference (NPSC), 2014. [cited 17.2.2018.] Available at: https://doi.org/10.1109/NPSC.2014.7103848.

[104] Siddiqui, B. A. et. al. "A Versatile Solution for Continuous On-line PD Monitoring" [online]. Conference paper. Innovative Smart Grid Technologies - Asia (ISGT ASIA), 2015. [cited 19.2.2018.] Available at: https://doi.org/10.1109/ISGT-Asia.2015.7387157.

[105] Mehairjan, R. P. Y. A. et. al. "Experiences with the Introduction of Online Condition Monitoring in Asset Management for Distribution Networks" [online]. Conference paper. International Conference on Condition Monitoring & Diagnosis, 2014. [cited 19.2.2018.] Available at: https://doi.org/10.13140/2.1.4241.2806.

[106] Shafiq, M. et. al. "Performance evaluation of PD monitoring technique integrated into medium voltage cable network for smart condition assessment" [online]. Conference paper. Electric Power Quality and Supply Reliability Conference (PQ), 2014. [cited 20.2.2018.] Available at: https://doi.org/10.1109/MELCON.2016.7495349.

[107] Ylä-Outinen, A. "Techno-Economic Feasibility of Novel On-LineCondition Monitoring Methods in Low Voltage Distribution Networks". MSc. Thesis. Lappeenranta University of Technology, Faculty of Technology. 2012.

[108] Chrisou, S. et. al. "Setup and preliminary results of an Online Thermal Condition Monitoring System for MV Cable Joints" [online]. Conference paper. 18th Mediterranean Electrotechnical Conference (MELECON), 2016. [cited 20.2.2018.] Available at: https://doi.org/10.1109/MELCON.2016.7495349.

[109] Khan, A. A. et. al. "A Review of Condition Monitoring of Underground Power Cables " [online]. Conference paper. IEEE International Conference on Condition Monitoring and Diagnosis, 2012. [cited 20.2.2018.] Available at: https://doi.org/10.1109/CMD.2012.6416300.

[110] Finnish Standard Association SFS. "SFS-EN 50160 Voltage characteristics of electricity supplied by public electricity networks". SESKO Standardisation in Finland, 4th edition, 2010.

[111] Ding, F., Mather, B and Gotseff, P "Technologies to Increase PV Hosting Capacity in Distribution Feeders" [online]. Conference paper. IEEE PES General Meeting. Boston, Massachusetts, 2016. [cited 27.12.2017.] Available at: https://www.nrel.gov/docs/fy16osti/65995.pdf.

[112] Navarro-Espionosa, A. and Ochoa, L. "Increasing the PV hosting capacity of LV networks: OLTC-fitted transformers vs. reinforcements" [online]. Conference paper. IEEE/PES Innovative Smart Grid Technologies ISGT, 2015. [cited 27.12.2017.] Available at: https://doi.org/10.1109/ISGT.2015.7131856.

[113] Finnish Standard Association SFS. "SFS-EN 50438 Requirements for micro-generating plants to be connected in parallel with public low-voltage distribution networks". SESKO Standardisation in Finland, 2nd edition, 2015.

[114] Finnish Energy. Verkostosuositus YA9:13, "Mikrotuotannon liittäminen sähkönjakeluverkkoon" [online]. Network recommendation. 2016. [cited 27.12.2017.] Available at: https://energia.fi/files/762/Mikrotuotannon_liittaminen_sahkonjakeluverkkoon_YA9_13_verkostosuositus_paivitetty_20160427.pdf.

[115] Suurinkeroinen, S. "Aurinkovoimalan haasteet haja-asutusalueella" [online]. Conference presentation. Urakoitsijapäivä 2016, Kouvola. Kymenlaakson Sähkö Ltd. [cited 27.12.2017.] Available at: https://www.ksoy.fi/sahkonsiirto/urakoitsijapalvelu/muut-tekniset-ohjeet.